The LEAPTech Experiment

Approach
Results
Recommendations

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Executive Summary

Approach

The LEAPTech experiment was an ambitious initial foray into Airframe-Propulsion Interaction (API) analysis, design, and testing

- Approach was akin to George Mueller’s Apollo “All-Up Testing” philosophy
    - New design / analysis regime -- CFD of the API configuration
    - New propulsion system -- Batteries / controllers / motors / propellers
    - New testing approach -- Truck-based lakebed “wind tunnel”
- “All-Up Testing” carries inherent risk
- Failure is an option

Results

Four illustrative examples:

- Inability to accurately control or accurately measure the test condition
- Large experimental uncertainties
- Multiple CFD analyses not yet converged to a single answer
- Experiment configuration yielded a nonlinear environment with significant contaminatory AC signal components

Executive Summary

Recommendations

- Consider LEAPTech as a valuable exercise in identifying PAI areas requiring additional investment

- Consider a back-to-basics, foundational, incremental approach
  - Demonstrate success on a much simpler configuration first, before moving to the multi-engine-wing or complete-aircraft problem
    - Experimentally
    - Analytically
  - Evaluate a larger suite of analytical tools for PAI applicability, before selecting one for production use
  - Leverage existing wind tunnel and other data sets for code validation

LEAPTech Lakebed Test Configuration

- Truck Testing Configuration
  - Bolted Joints -- on supporting trusswork
  - Airbag suspension -- to reduce transmitted road vibration
  - Water Ballast Tanks -- to lower Center of Gravity
  - Sway Braces -- to constrain airbag lateral displacement

- Force and Moment Instrumentation
  - Load Cells
    - Lift / Pitch / Roll Load Cells (4 each -- overconstrained)
    - Drag / Yaw Load Cells (2 each)
    - Lateral Load Cell (1 each)
- AOA Adjustment (2 each)

Testing in “Calm” Weather Conditions

Metek anemometer measures 3D winds at 20 samples/sec

As defined by NOAA:
https://www.aviationweather.gov/static/help/taf-decode.php

“Calm winds (three knots or less) are encoded as 00000KT”

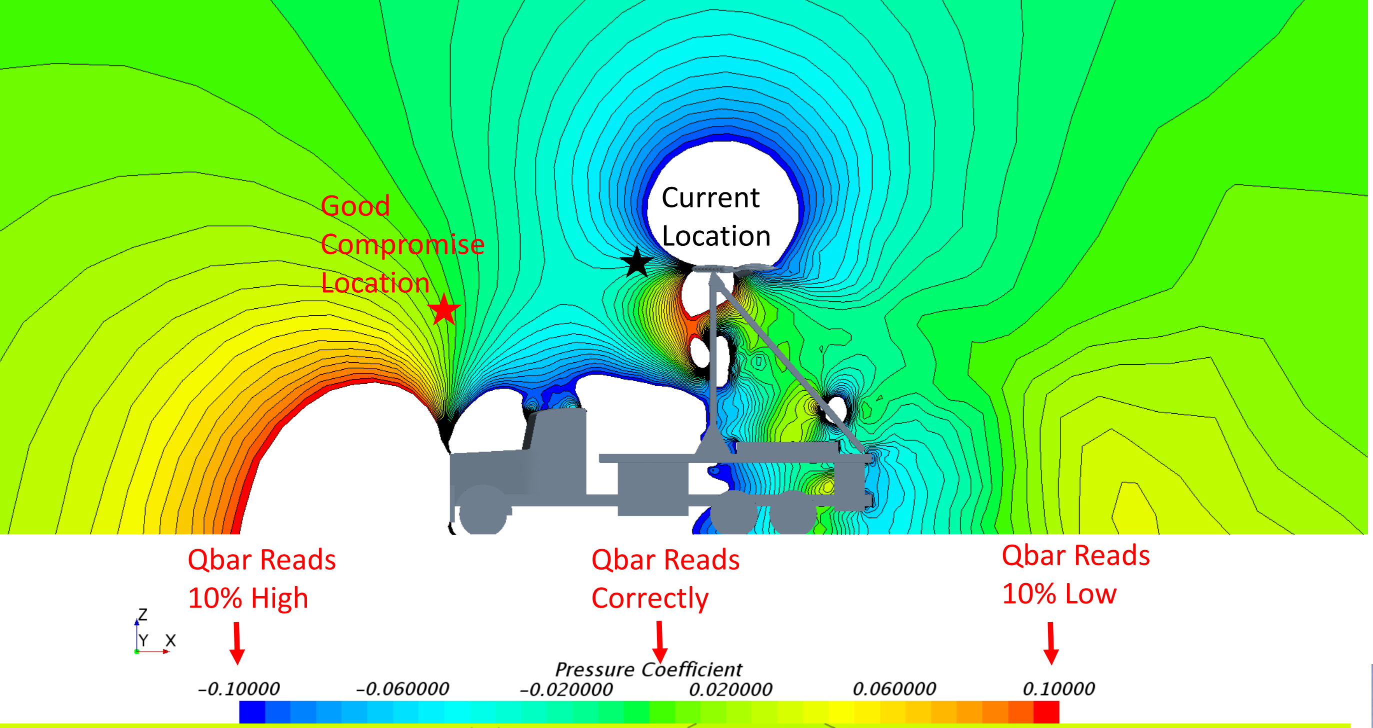
- Murray’s personal observation is that EAFB winter winds below 2 MPH are insensible
- But our Metek ultrasonic anemometer can measure winds well below 3 kts (it uses time-of-flight, not rotating elements)

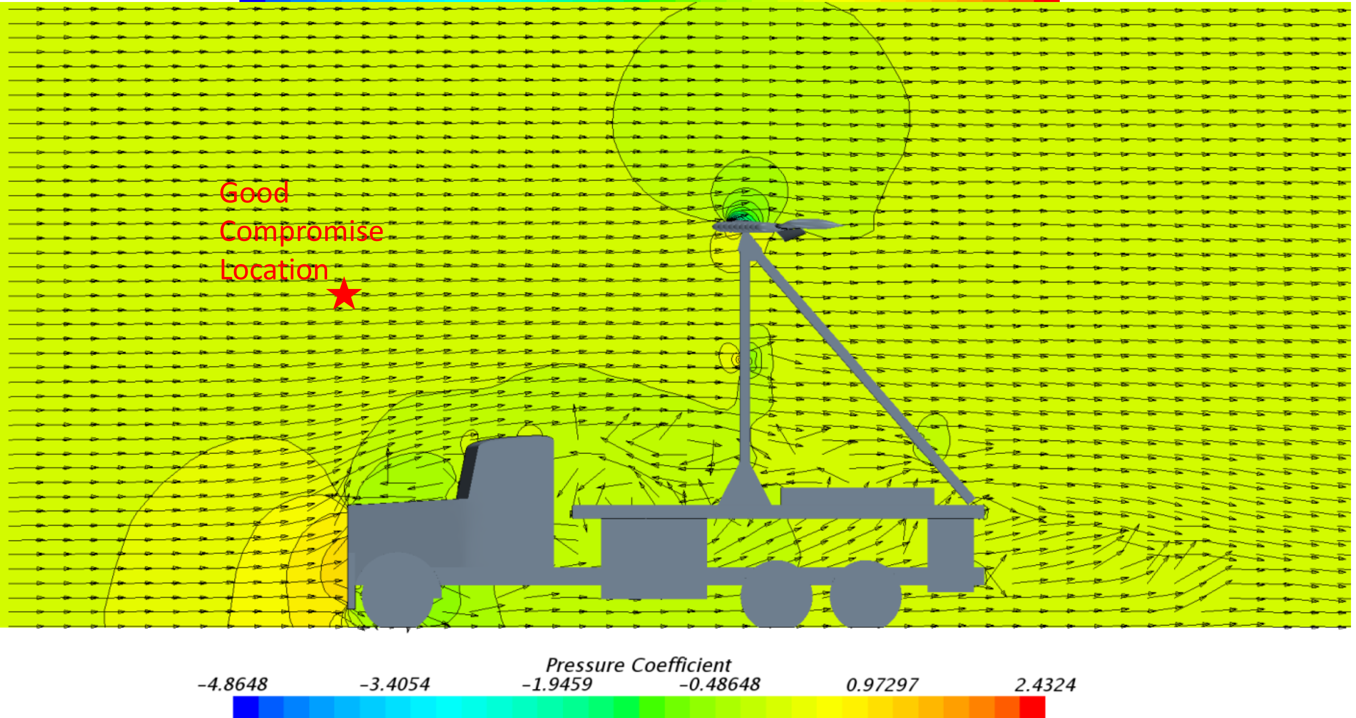
- At our 73 MPH test condition:
  - +/- 3 knots headwind yields +/- 9.7% in dynamic pressure
  - +/- 3 knots crosswind yields +/- 3.5 deg beta
- Oct 15 2015, a “good” test day, we observed spatial and temporal variations in winds on ~1 mile and ~1 minute scales:
  - Observed +1 to +2 deg beta AND -2 to -3 deg beta on the same runway pass
- 4 “Primrose Paths” to avoid:
  - Testing at low airspeed, unless you have 100% control of the test condition (wind tunnel)
  - Qualitative assessment that “calm” weather conditions mean zero winds
  - Averaging results from “upwind” and “downwind” passes
  - Using measured winds in vicinity of the testing runway in place of relative wind on the test vehicle itself

Operational Scenario
Airdata Measurement System

- 12000-foot runway with anemometer near each end
- GPS truck speed minus measured winds provides low-frequency component of airspeed
- Wing-mounted airdata probe provides high-frequency component of airspeed
- Both signals were blended for final airspeed estimate

CFD for Selection of Airdata Measurement Location

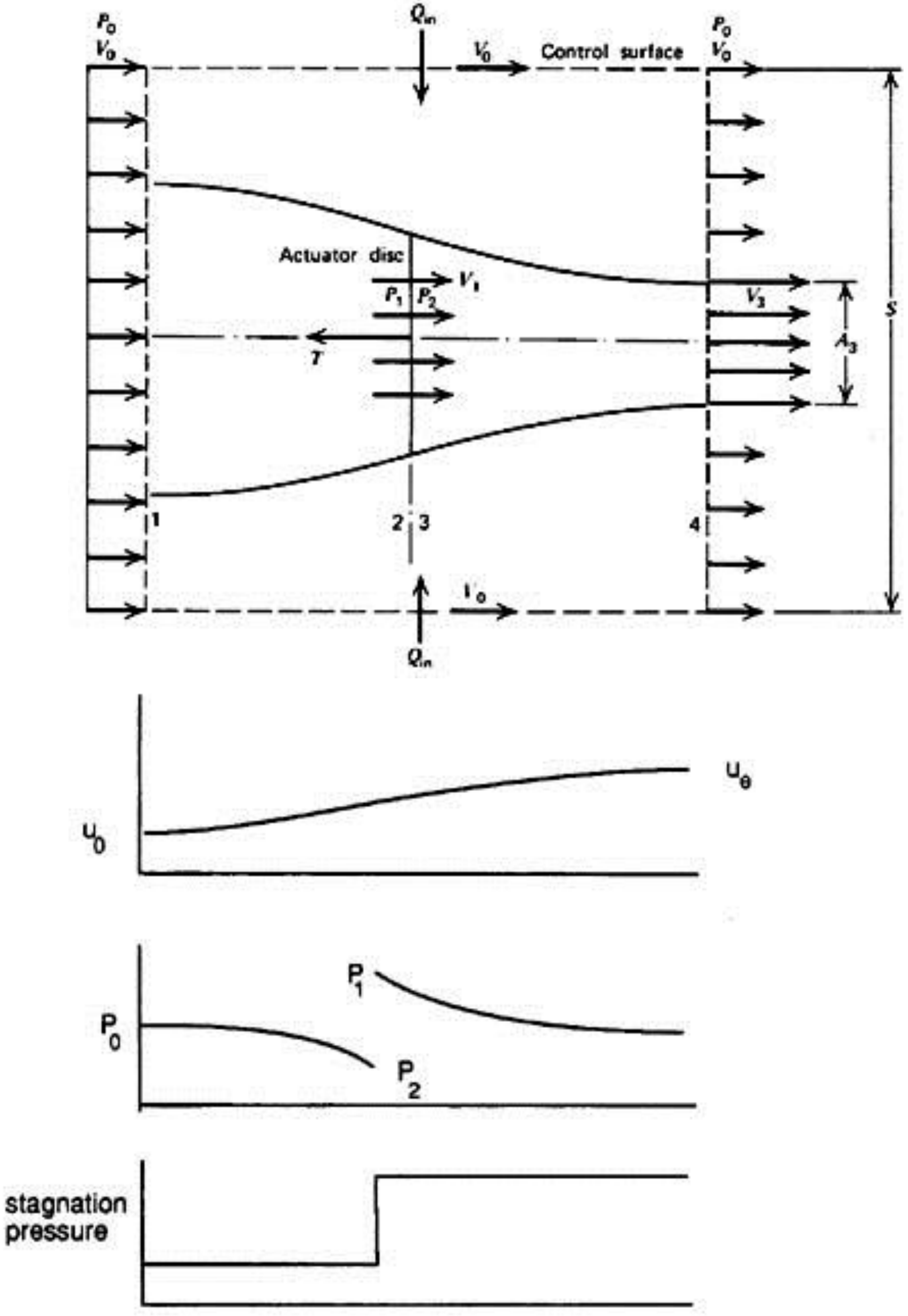




Desirable attributes:

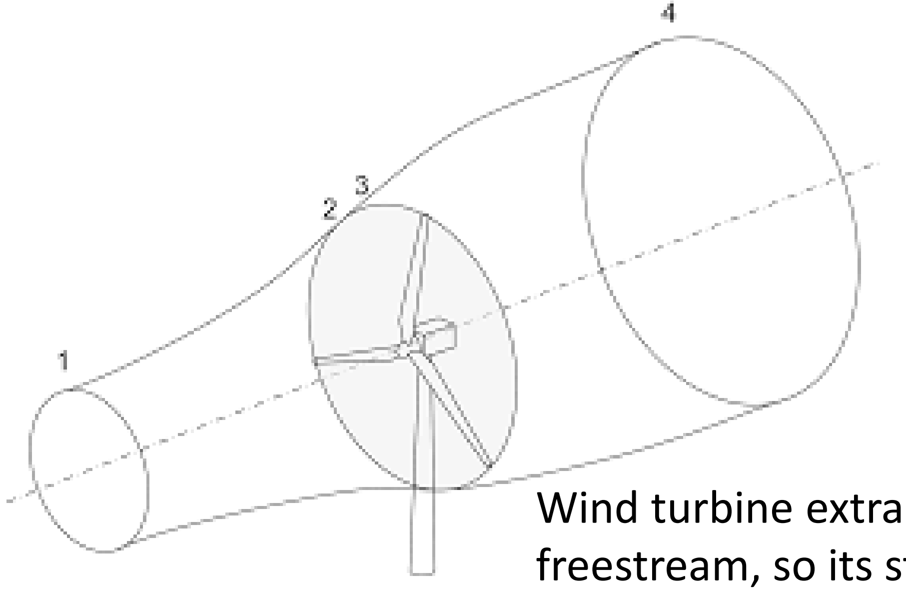
- Cp = 0 (V_local = V∞)
- Low pressure gradients
- Low flow angularity
- Invariant with wing AOA
- Short, faired support shaft

In 1983, they didn’t have the benefit of CFD for airdata probe location selection



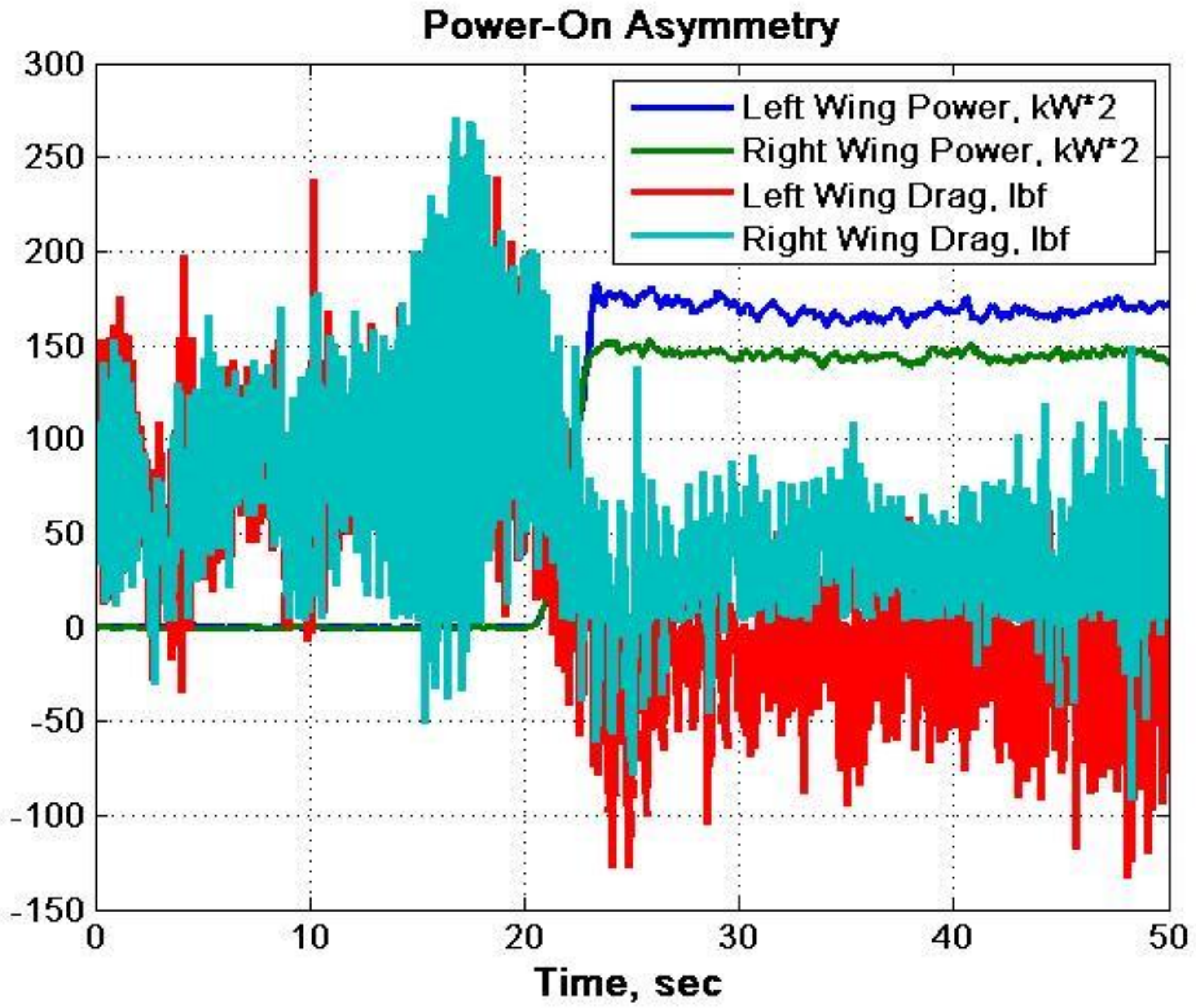
Actuator Disk Modeling of Propeller

- In CFD, propulsive energy is added to the flow at the propeller disk and combined as a boundary conditions in CFD:
  - Streamwise Force (thrust)
  - Tangential (torque)
- Shaft power values “mapped” to estimated thrust and torque coefficients
- No evidence that implementation was verified between LaRC and Joby (large uncertainty in drag between CFD results?)



Wind turbine extracts energy from the freestream, so its streamtube ~grows~ in diameter downwind

Propulsion System Asymmetry



- At the same RPM, the motors on left wing are absorbing about 15% more power than those on right wing
- 40 lbf estimated thrust imbalance despite noisy load cell signals
- 15 deg of rudder deflection is estimated (using flight-measured SCEPTOR rudder effectiveness) to correct the yawing moment created by thrust imbalance (about 240 ft-lbf)

Further investigation was not possible within program schedule and funding.

Other Test and Result Concerns

Inability to:

- Accurately control the test condition (truck did not have a working speedometer)
- Accurately measure the test condition

Large experimental uncertainties

Experiment configuration yielded a nonlinear environment with significant contaminatory AC signal components

Multiple CFD analyses not yet converged to a single answer

Conclusions

LEAPTech experimental results compromised by myriad error sources and omissions:

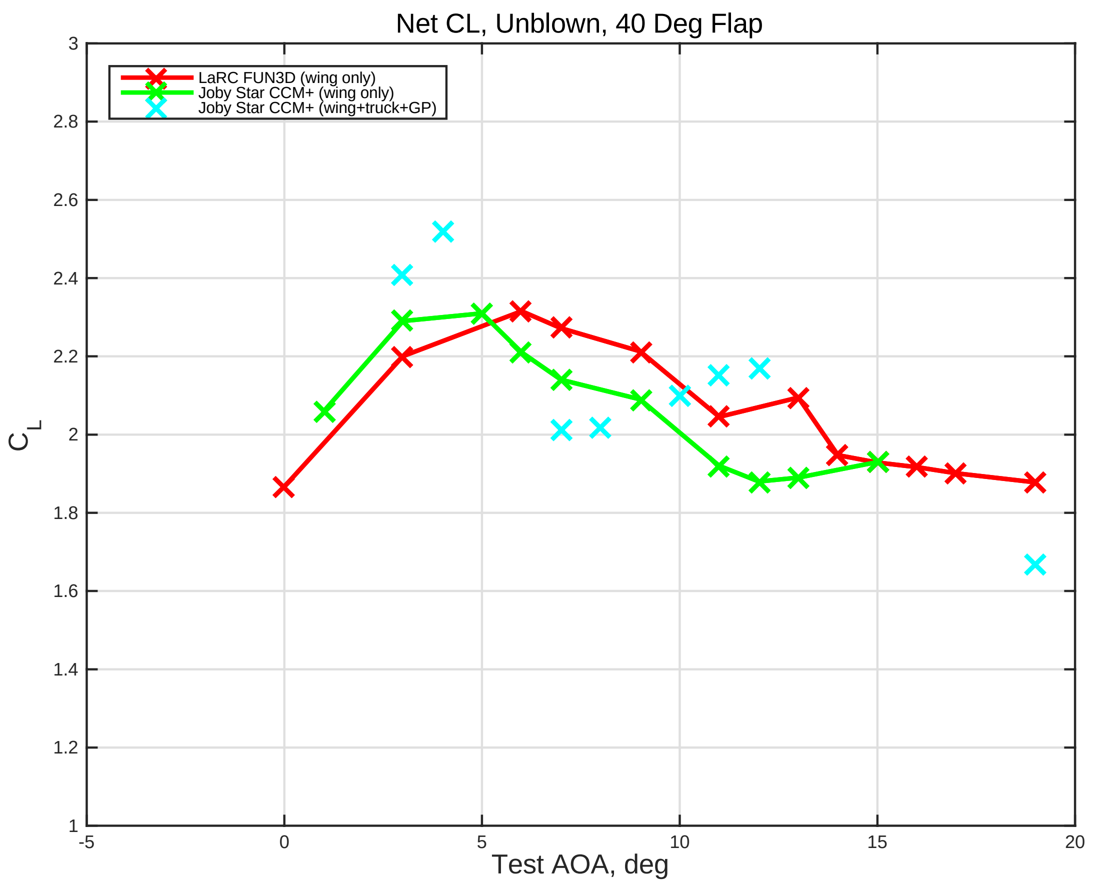
- Inability to accurately control or accurately measure airspeed and sideslip
- Asymmetric thrust
- Thrust unknowns
- Flow interference of truck, trusswork, and ground effects
- Uncalibrated and nonlinear force balance
- Relevant local-flow details not measured
- Presence of multiple and nonlinear AC excitation sources
- Aliasing? (probably) EMI? (more likely than in most experiments)

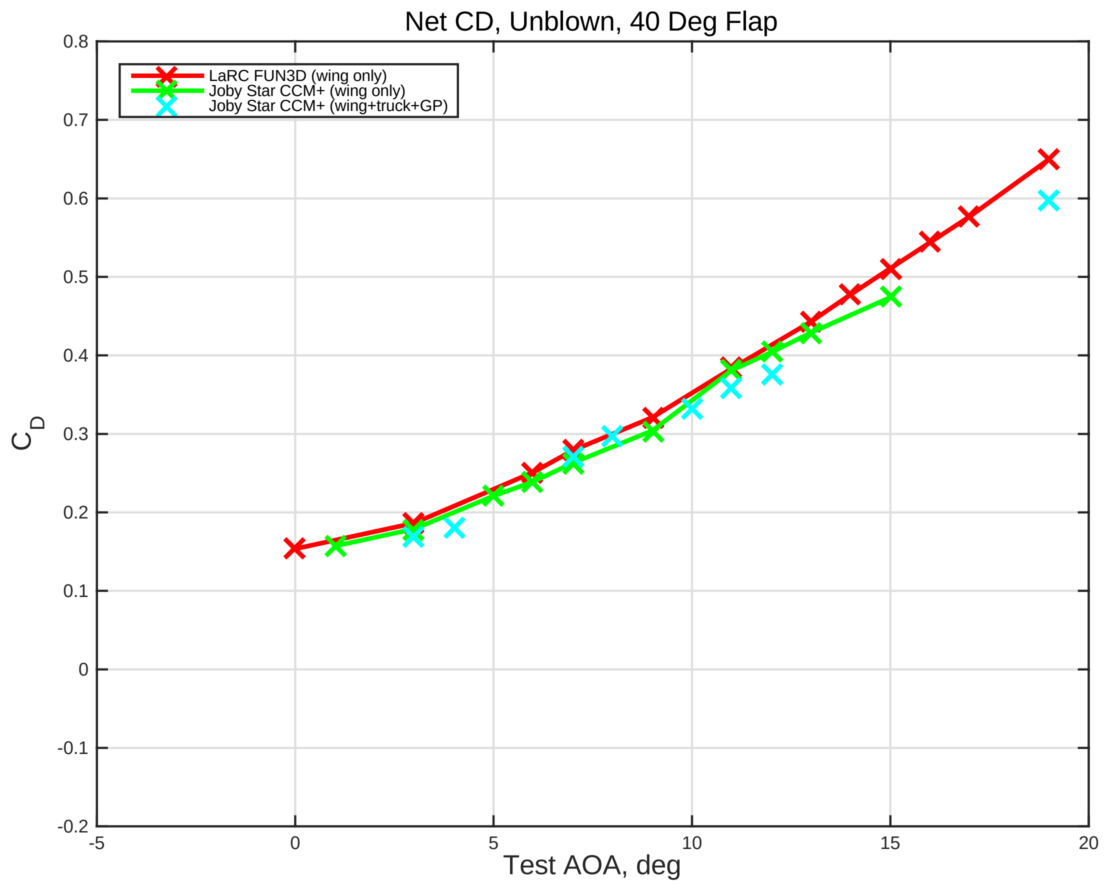
CFD at idealized conditions is not relevant for comparison with the LEAPTech experiment, due to overly optimistic modeling:

- Perfect control and knowledge of test airspeed, AOA, beta
- Perfect knowledge of geometry including measurement locations
- Symmetric propulsion system
- Perfect knowledge of thrust model
- No truck, trusswork, or ground effects

CFD solutions are not yet sufficiently converged for relevant comparison with ~any~ experimental results

Unblown Wing (Props Removed) -- Lift and Drag *Coefficients*





- These are CFD results for a variety of:
    - CFD tools
    - CFD analysts
    - Truck and groundplane implementations
- CL looks worse than CD

- Ellipses shows large 2D experimental uncertainty bounds
- CFD trends often dramatically different
- Joby ground-effect deltas questionable

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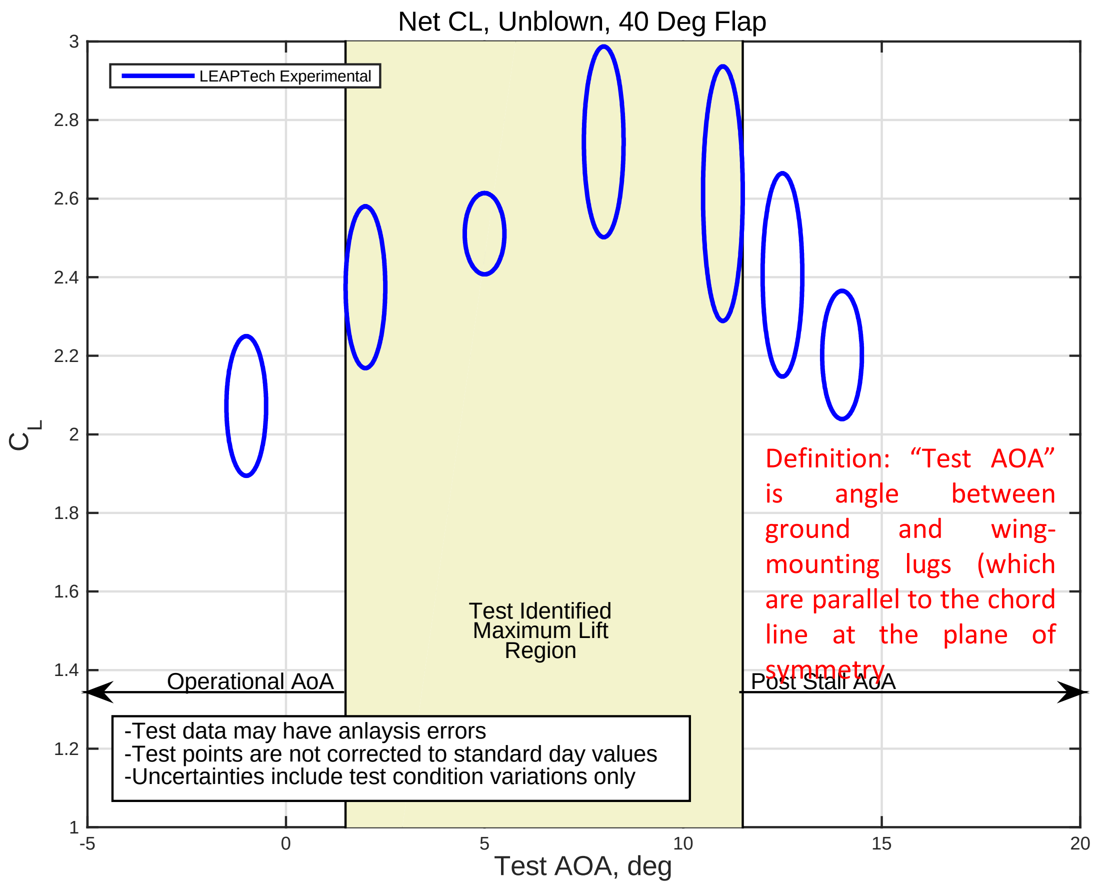

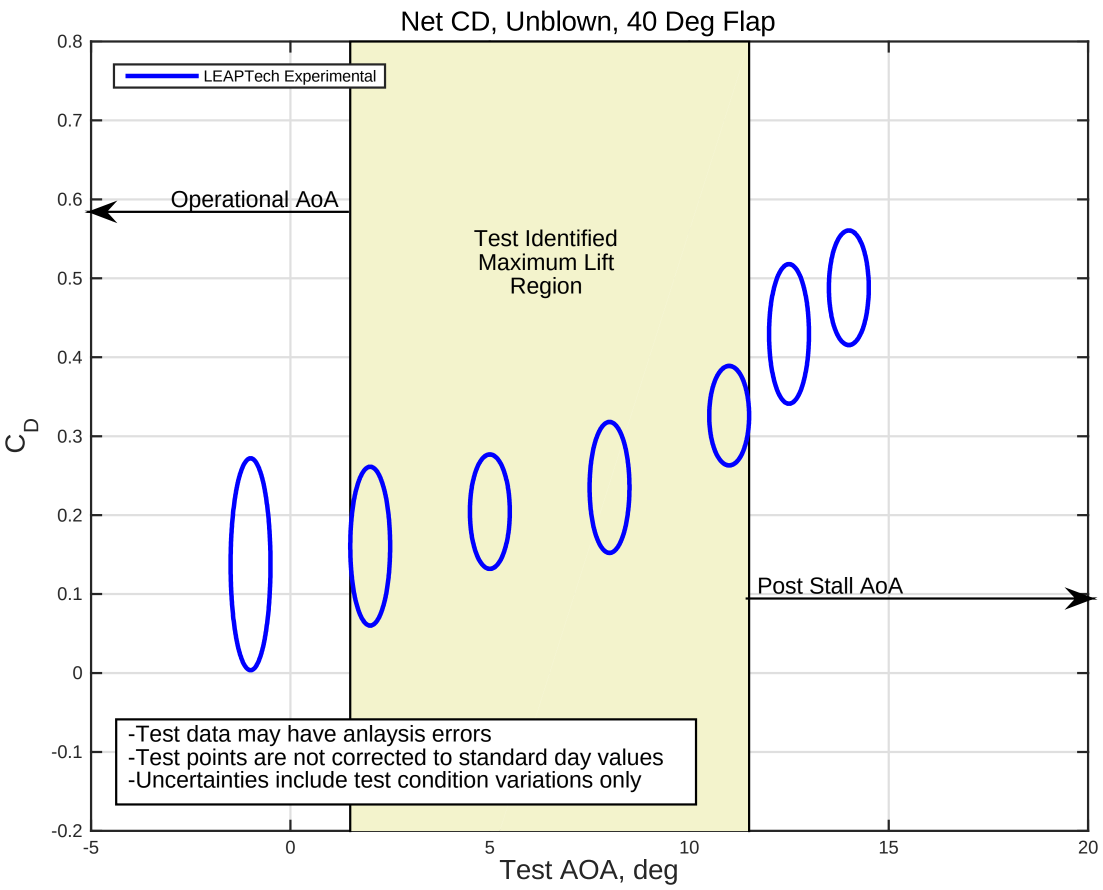

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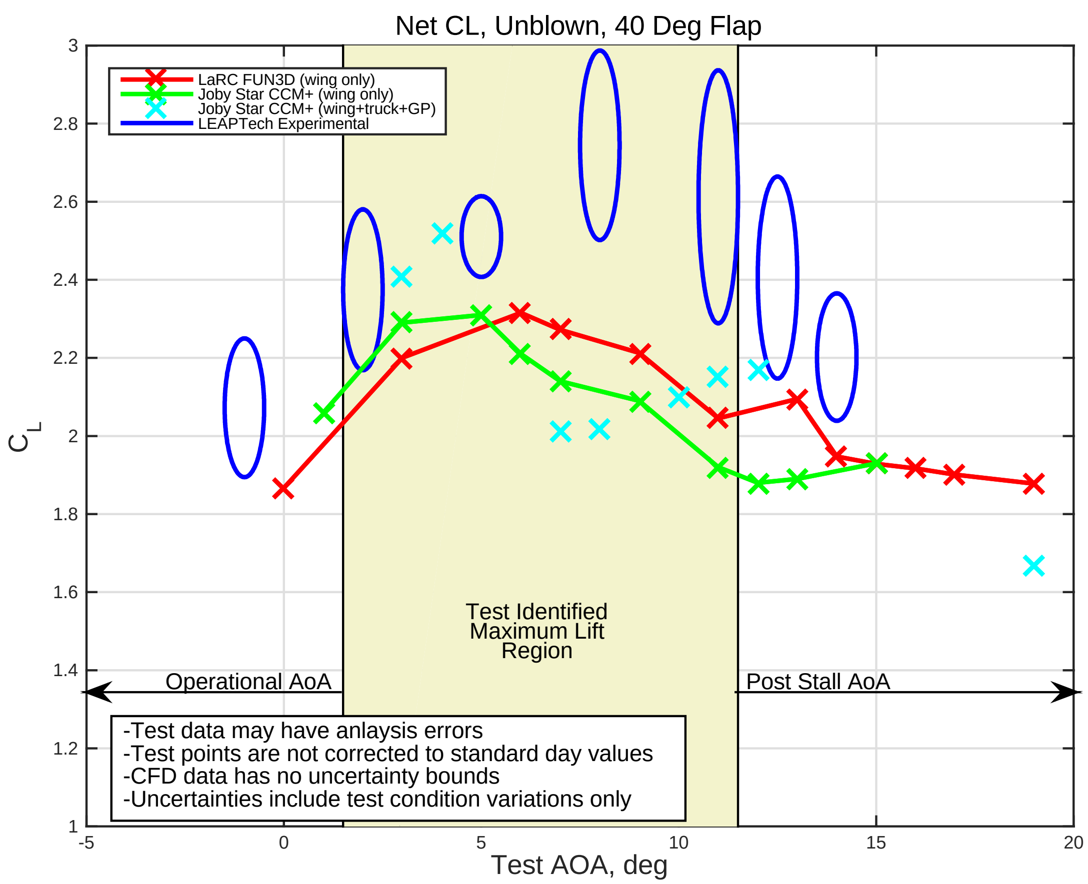

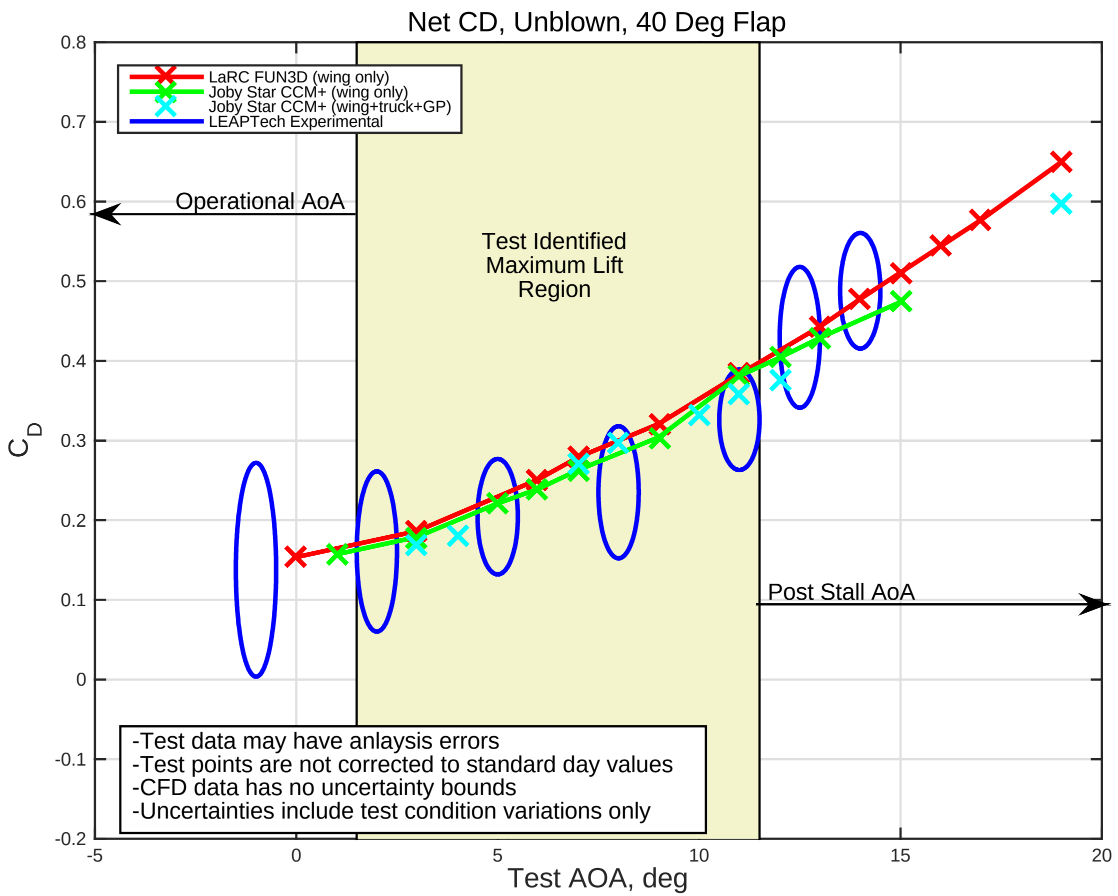

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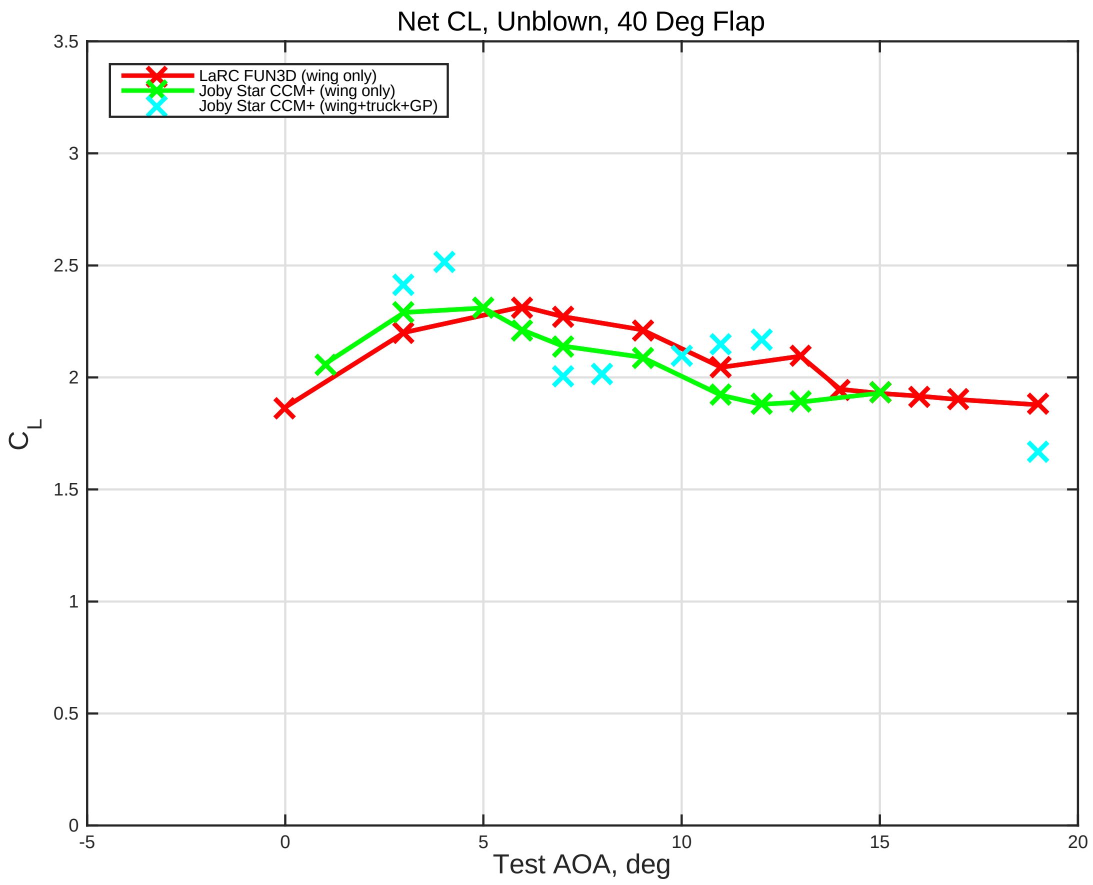

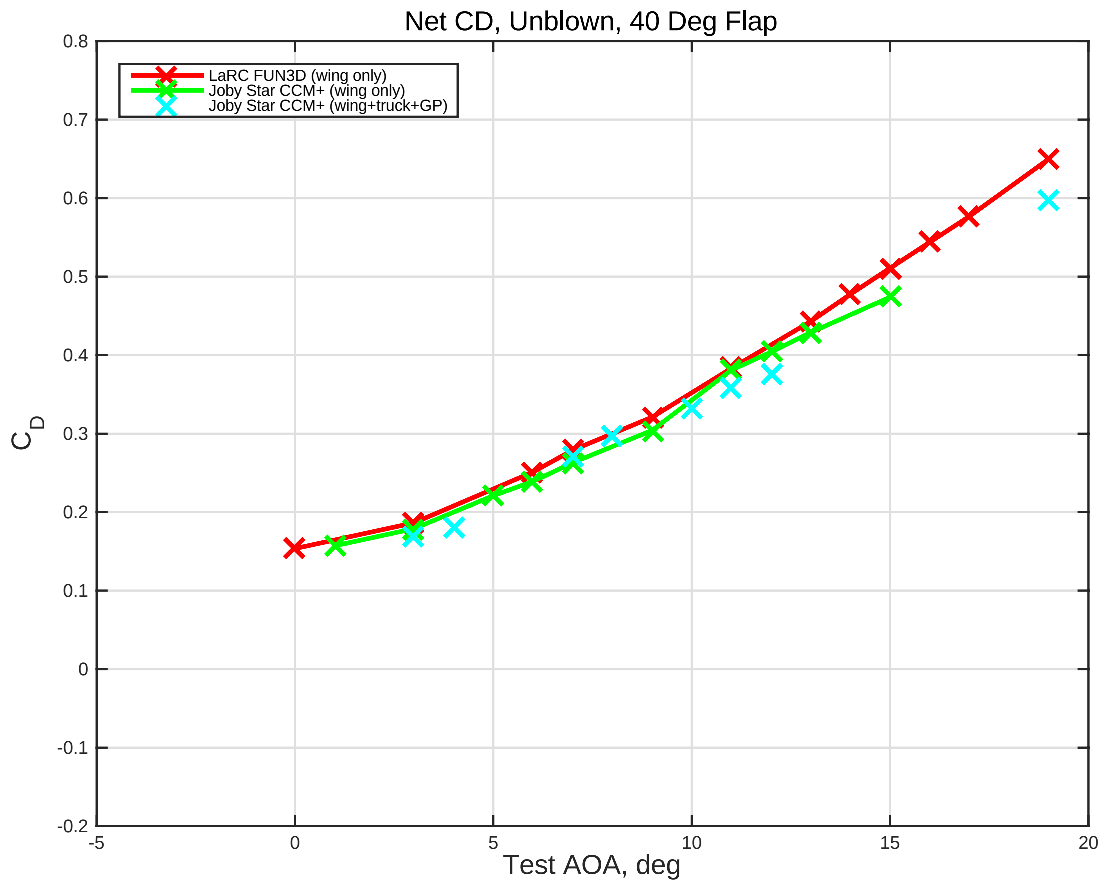

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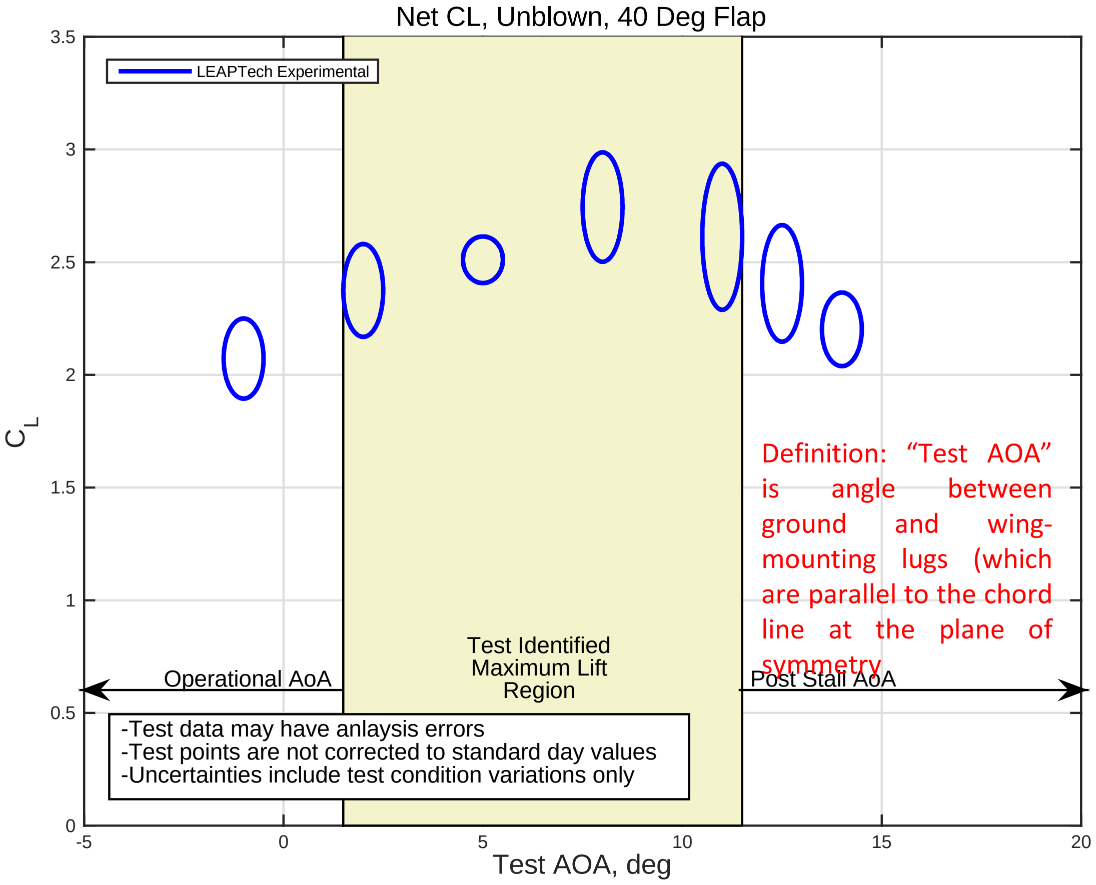

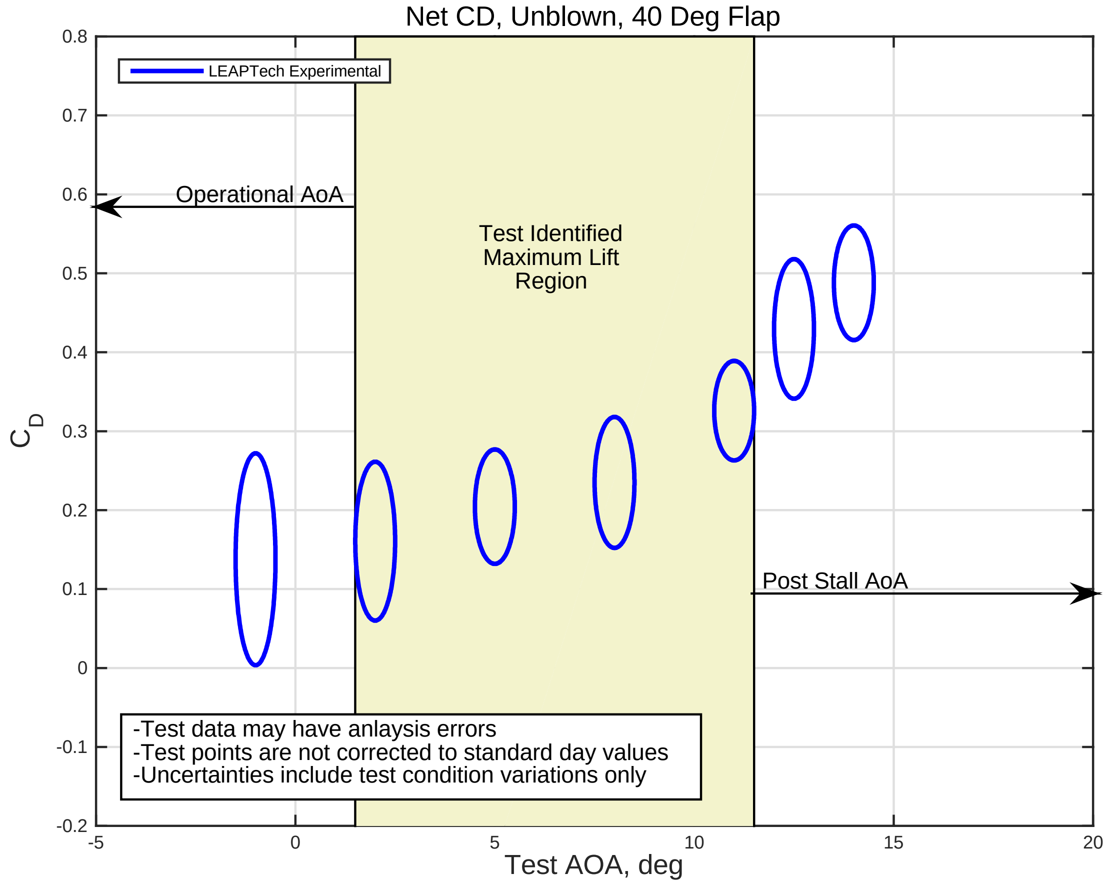

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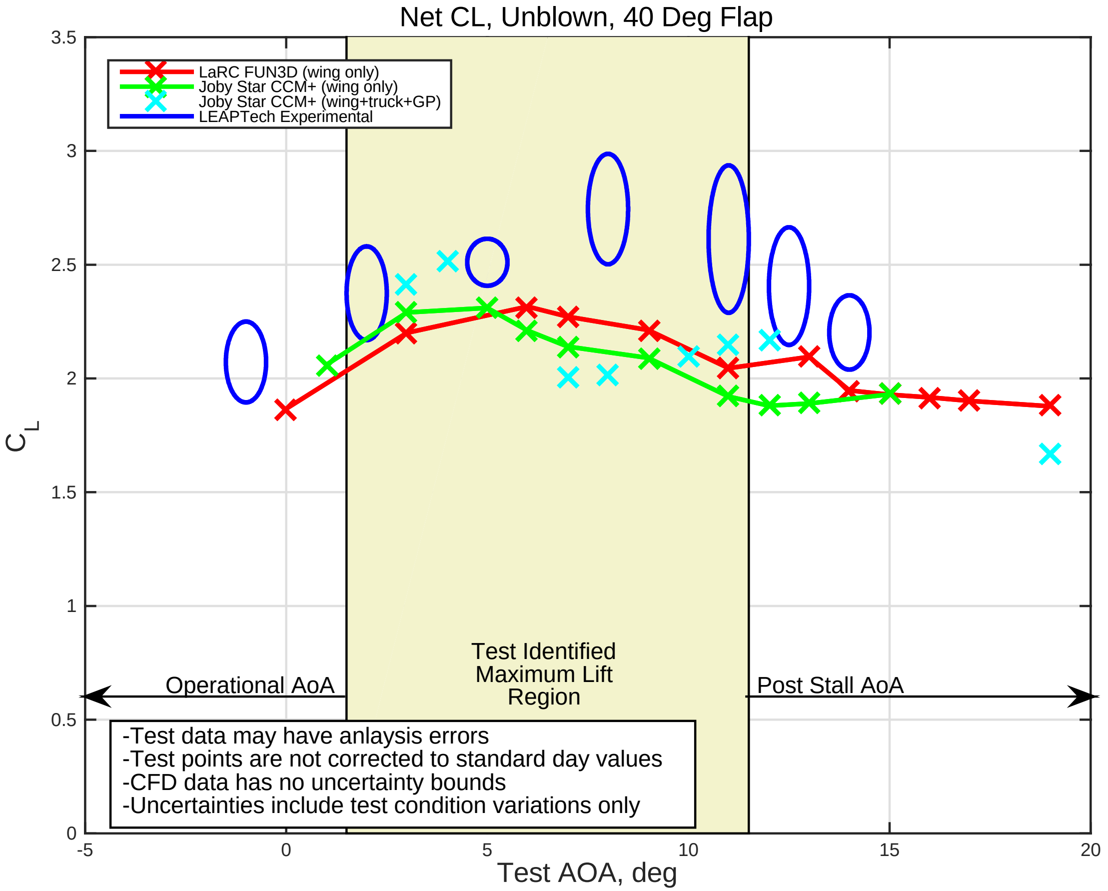

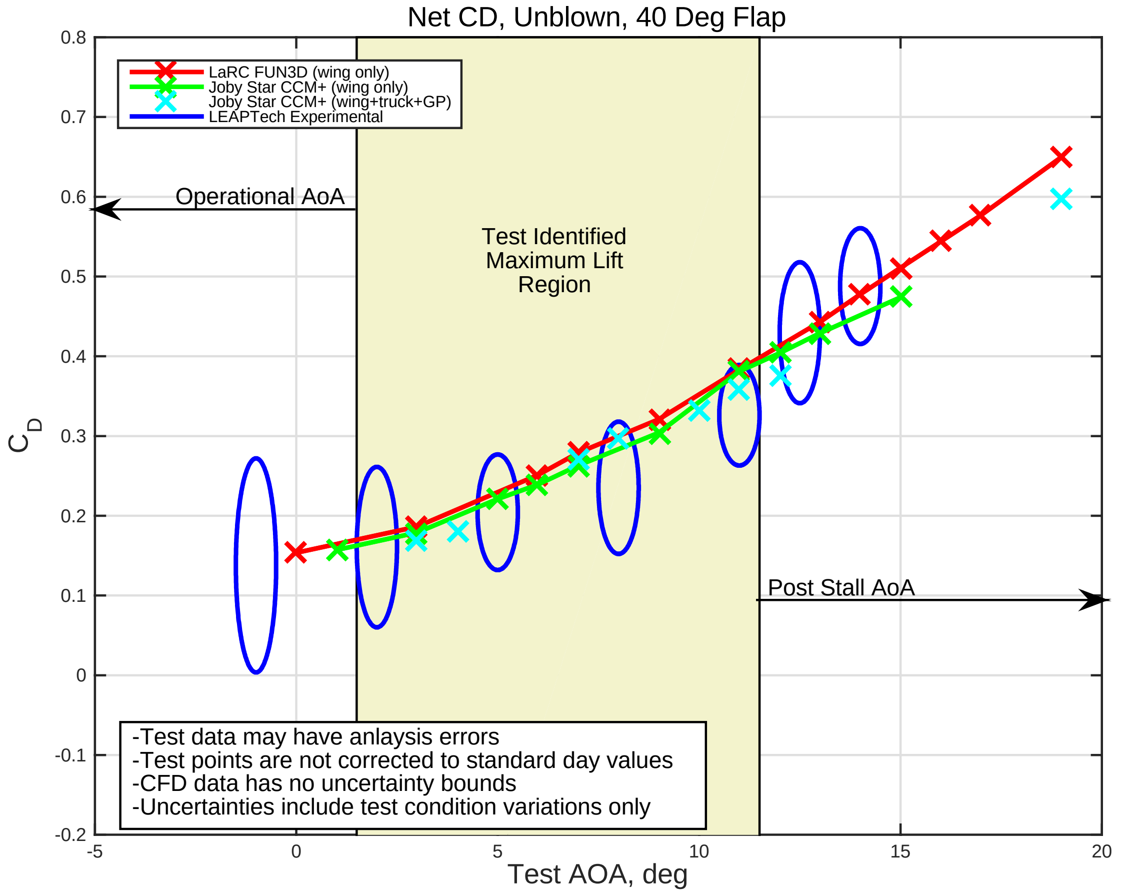

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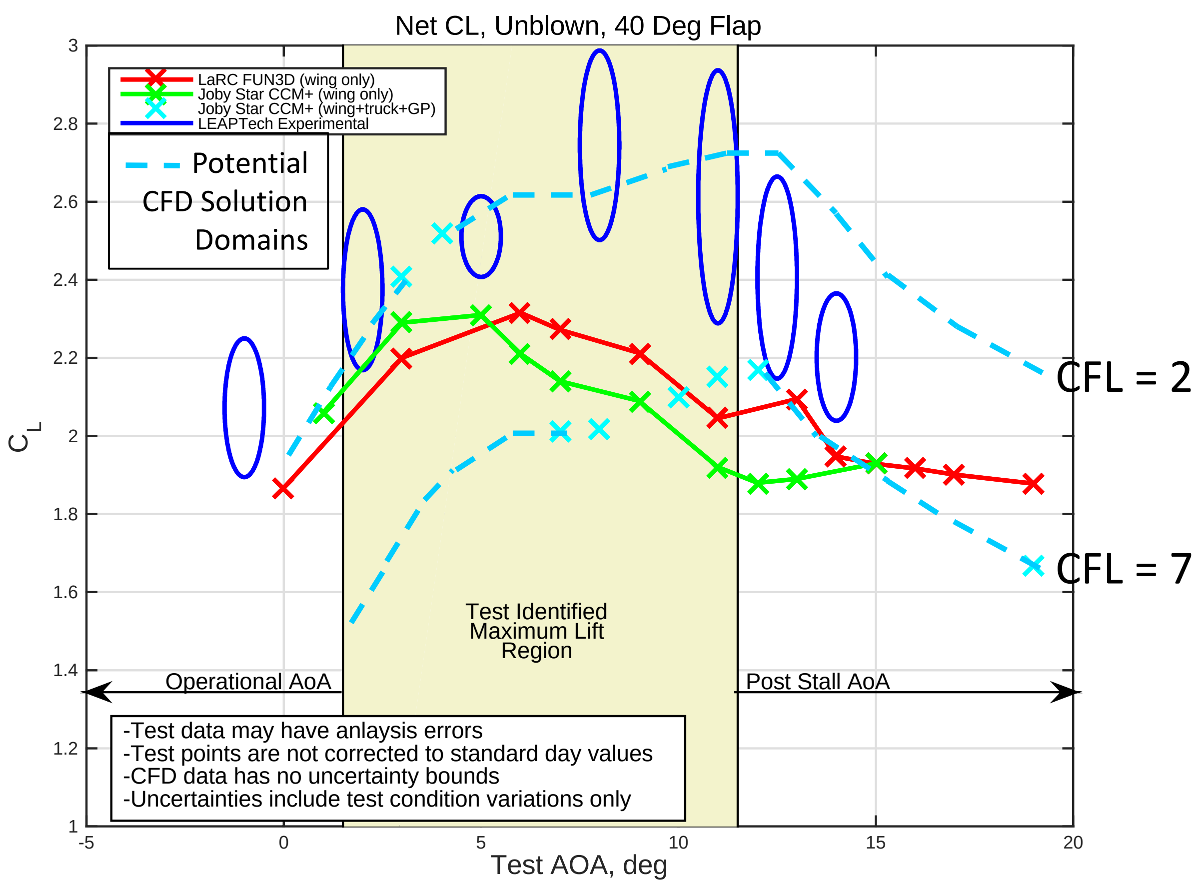
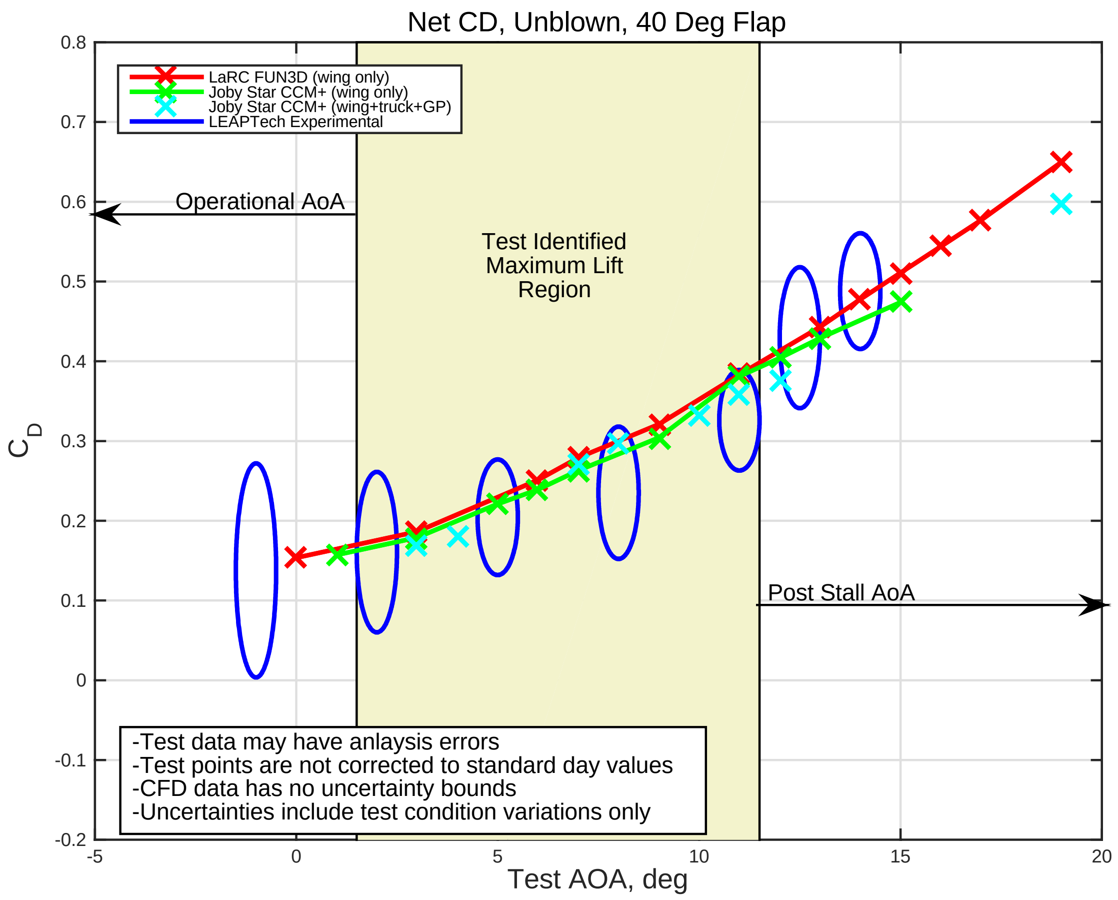




- Recent CFD work at AFRC indicates potential for bifurcation of CFD solution with sizing of solution time-step-size (CFL parameter)
- Which solution domain (if any?) is correct?

- In retrospect, the unblown 40 deg flap deflection was a probably a poor choice for CFD-to-experiment comparison

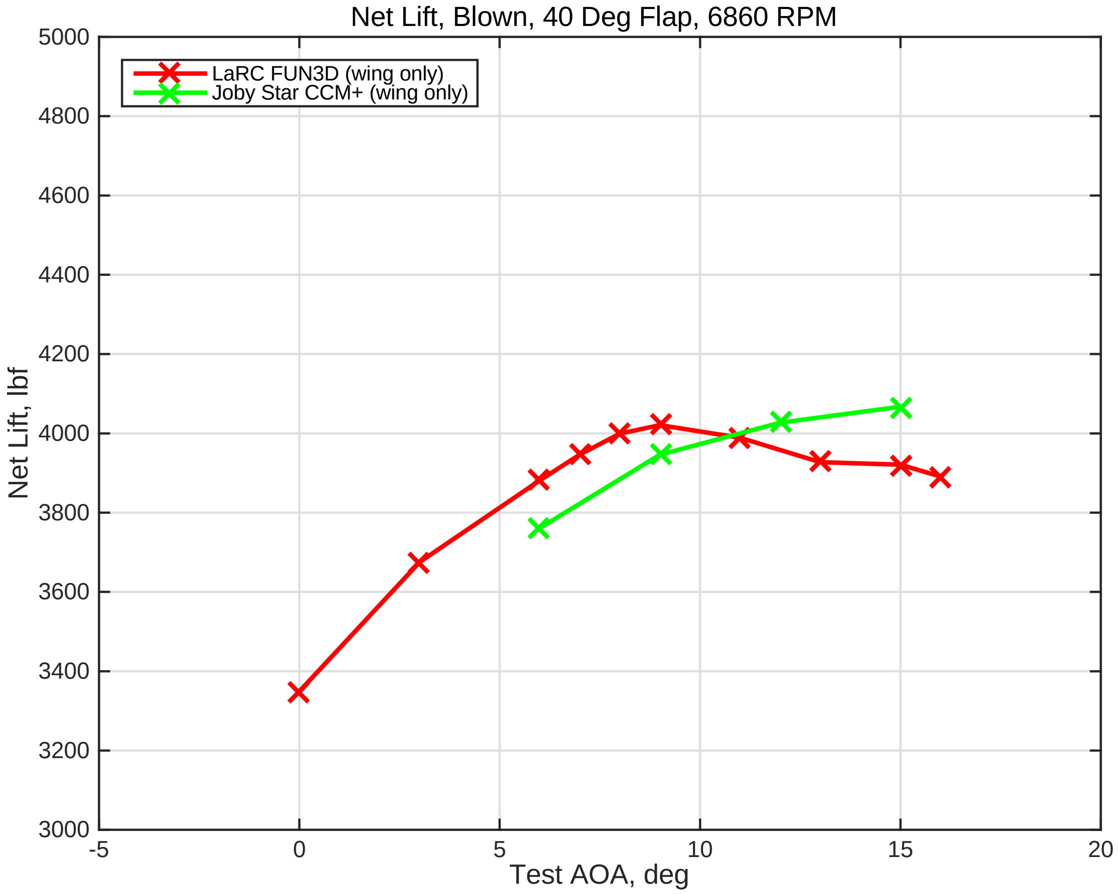
For Blown Wing, Better to Compare Lift and Drag Forces (not CL and CD) with CFD

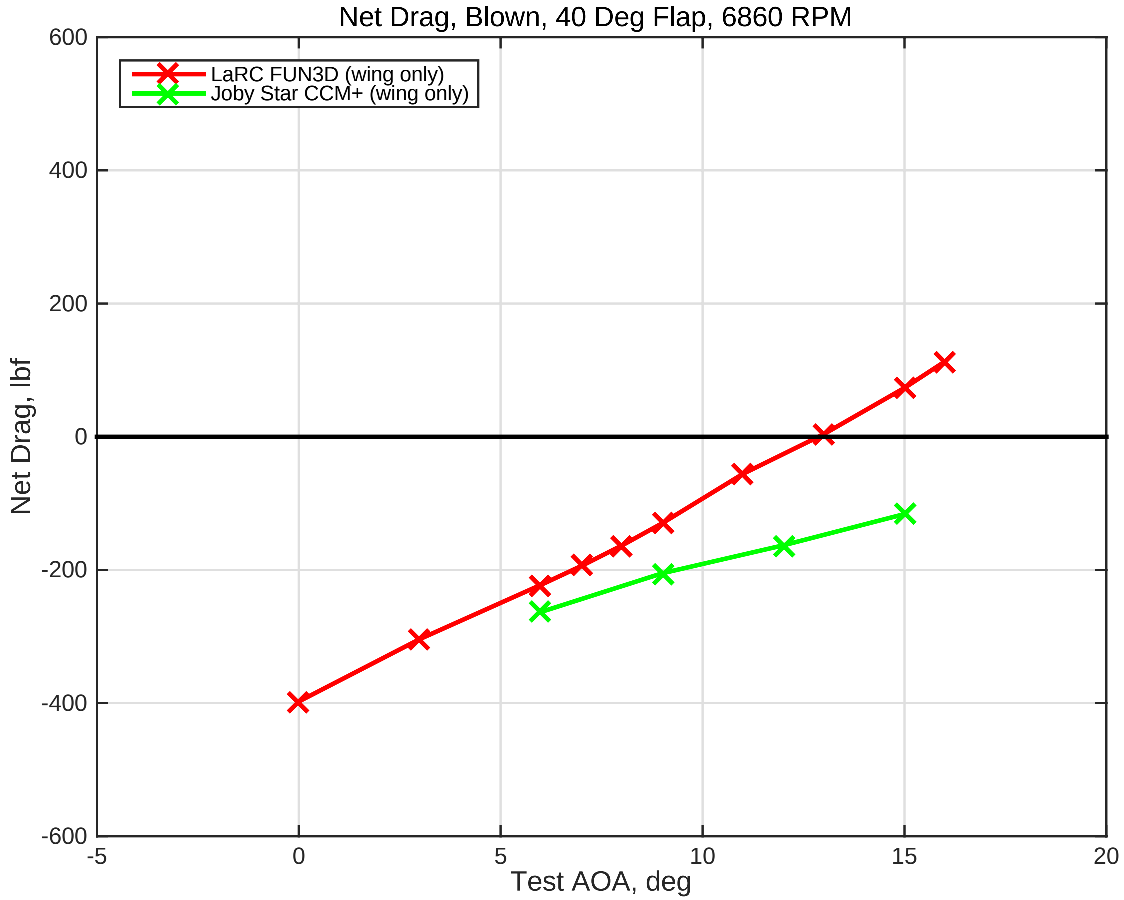
- For the unblown wing, CL and CD are essentially invariant with moderate changes in test airspeed
- True because at our test condition (M = 0.1, Re = 10^6), we are not near any M or Re “boundaries”
- So, if test dynamic pressure is a bit off-nominal – say 10% -- CL and CD will still be meaningful for comparison
- (This is one of the primary reasons for using nondimensional coefficients like CL and CD)

- **Not so for the blown wing**
- Blowing largely masks the wing from the effect of freestream dynamic pressure
- But . . . the freestream dynamic pressure is used for nondimensionalization
- With blowing, if the test dynamic pressure is a bit off-nominal, the CL and CD will be incorrect

- To protect oneself against errors due to nondimensionalization by a poorly-measured (incorrect) dynamic pressure, comparison of Lift and Drag is probably more meaningful than CL and CD

Blown Wing (Props Powered) -- Lift and Drag *Forces*





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- No CFD with truck or groundplane available
- CFD Lift comparisons converging
- CFD Drag discrepancies large
- First instance of measured lift below CFD

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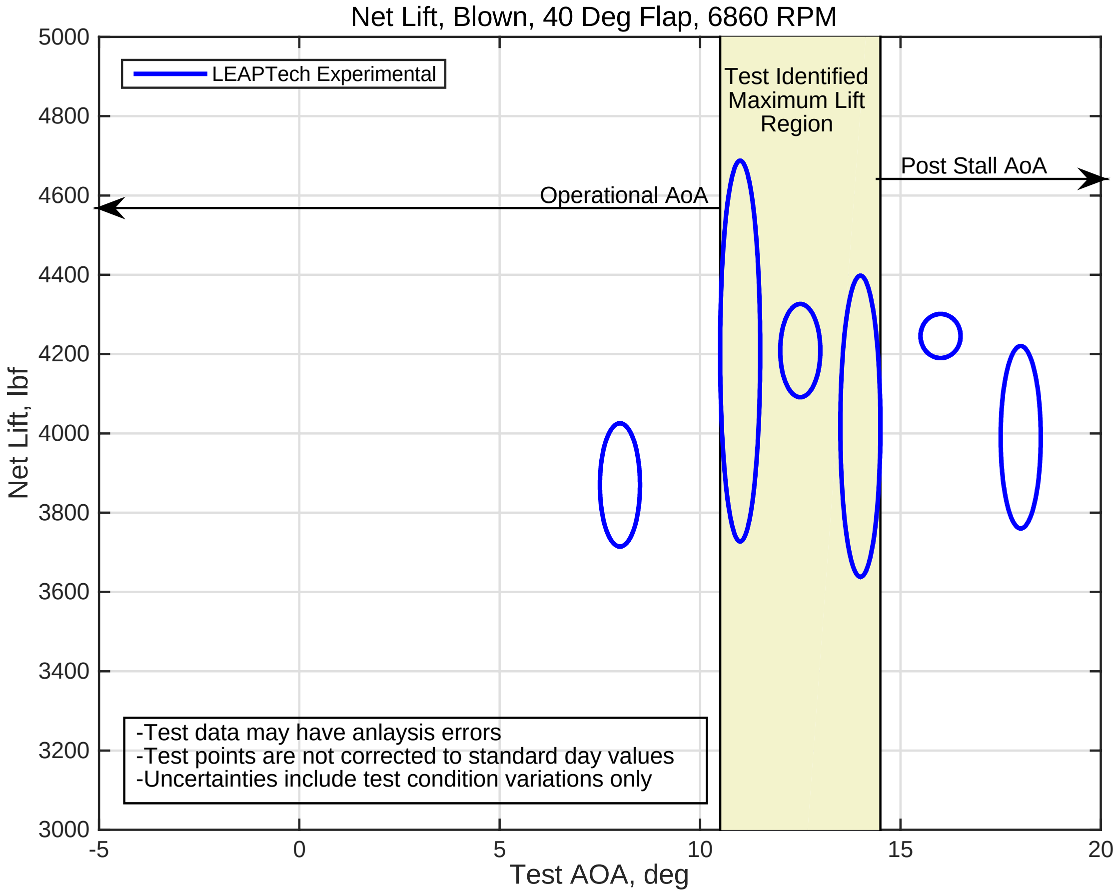

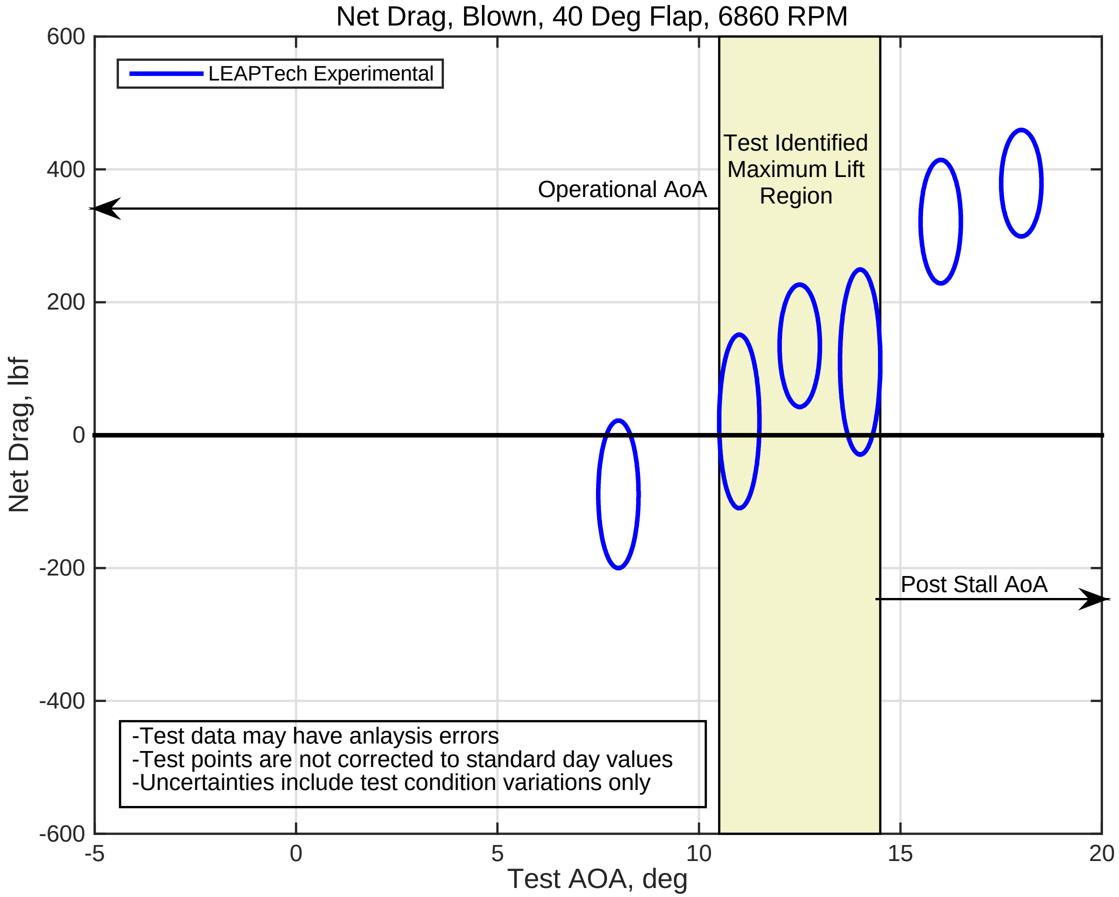

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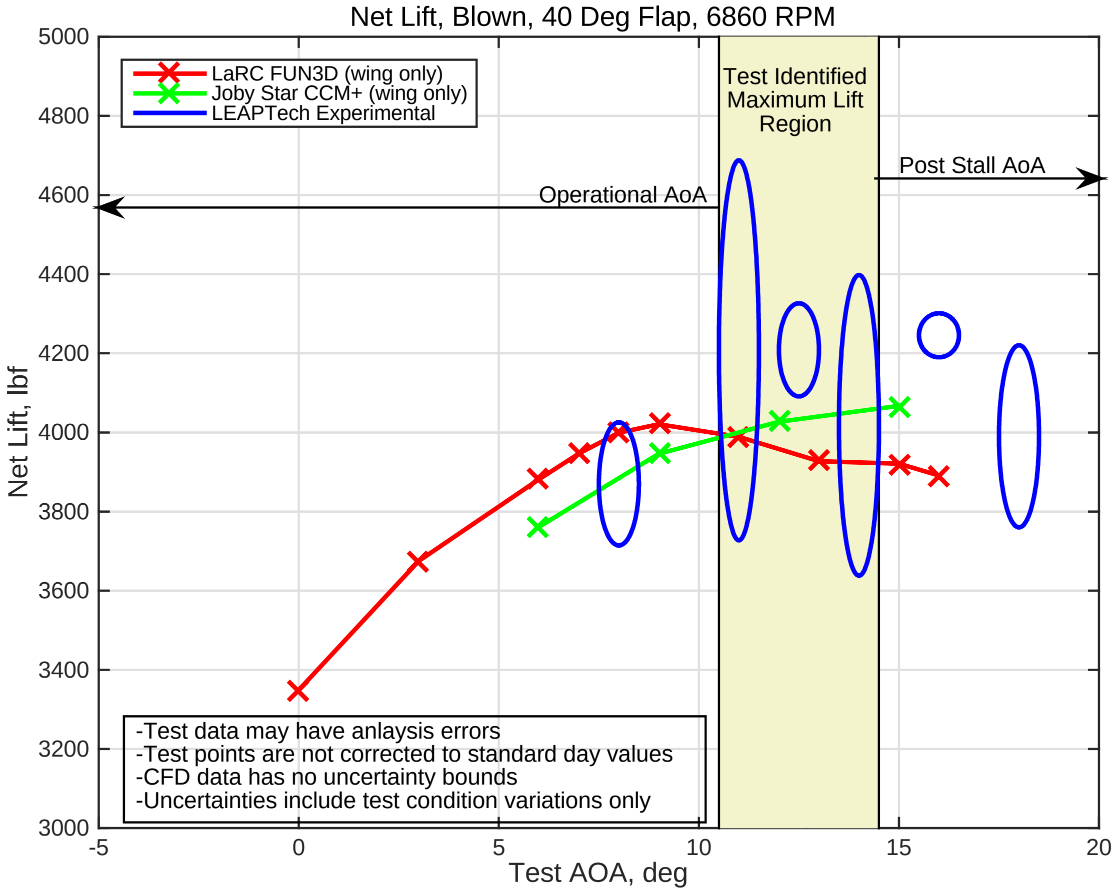

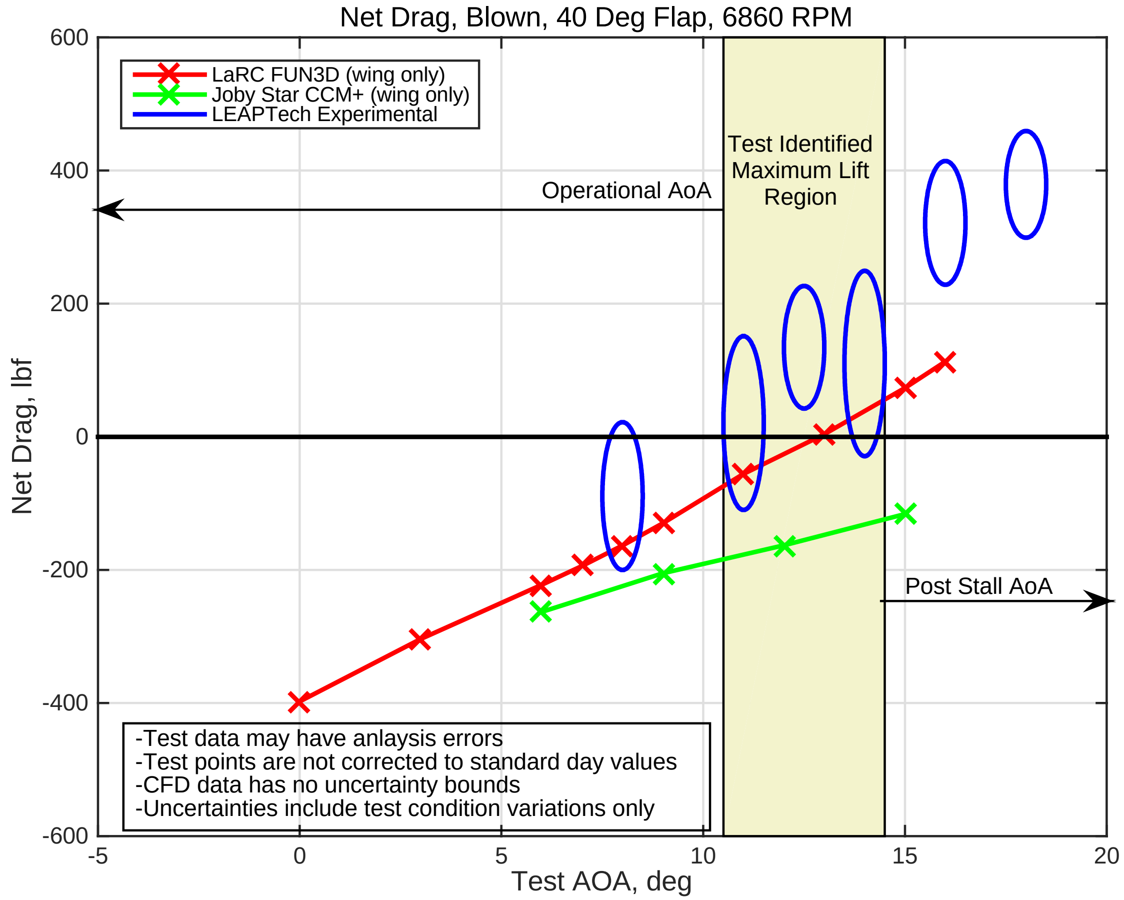

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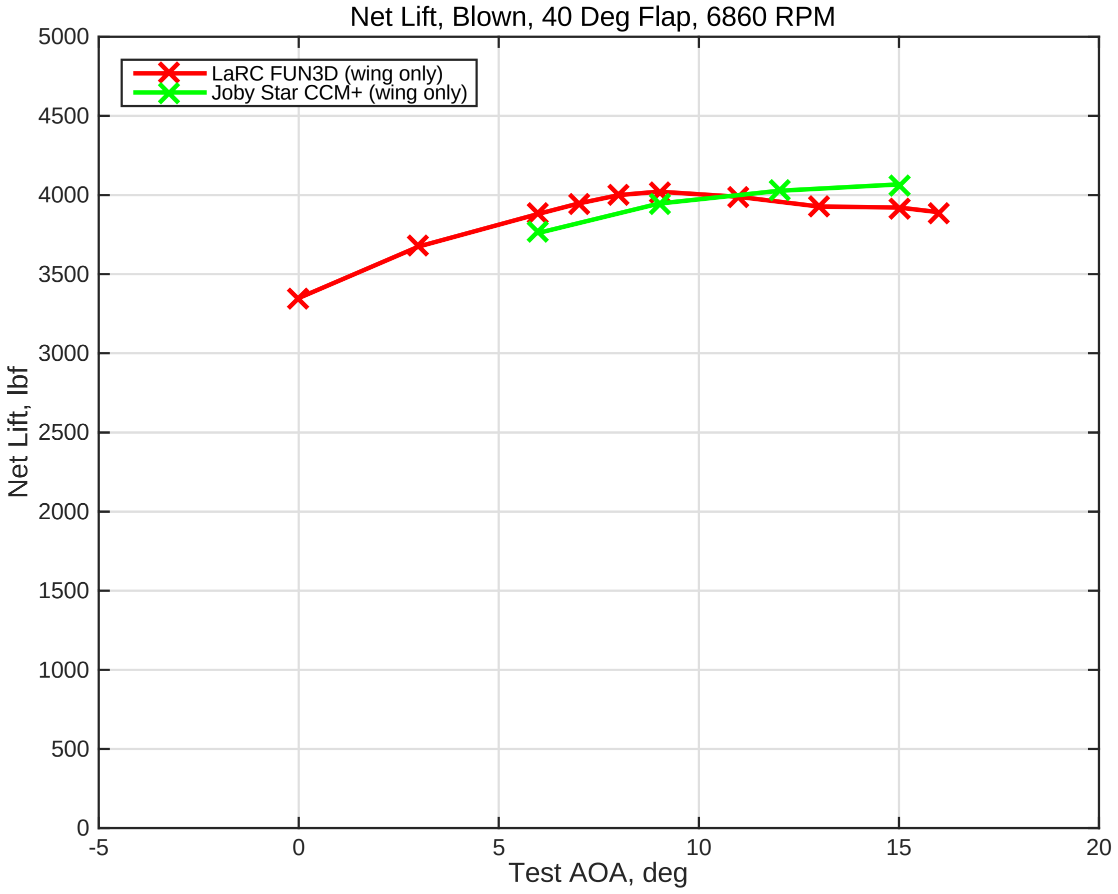

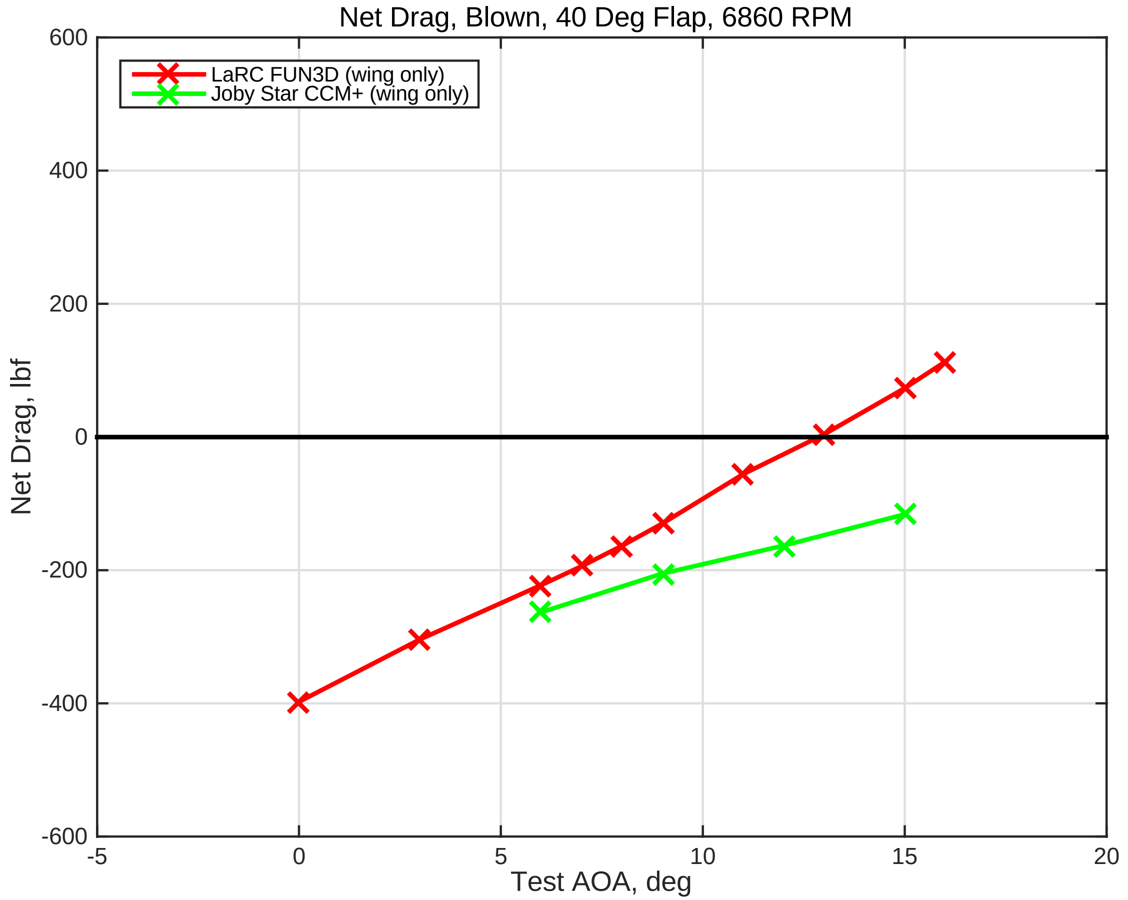

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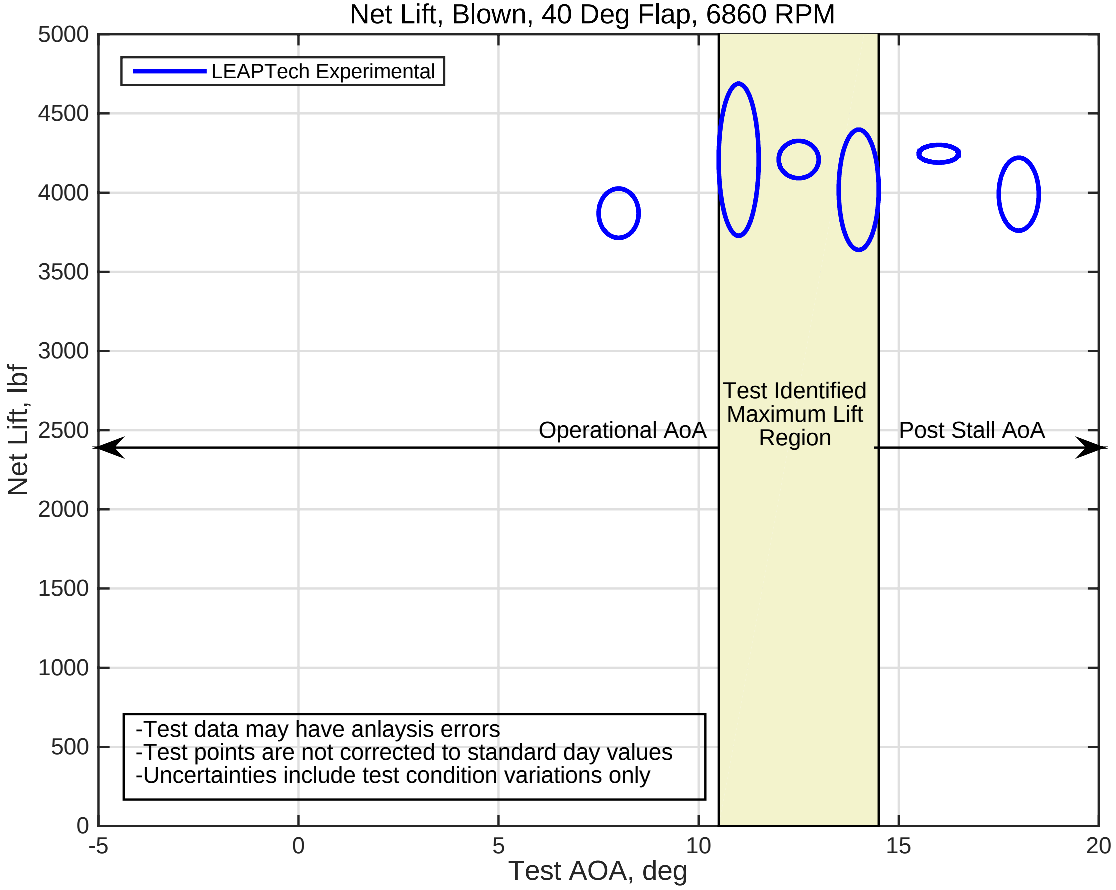

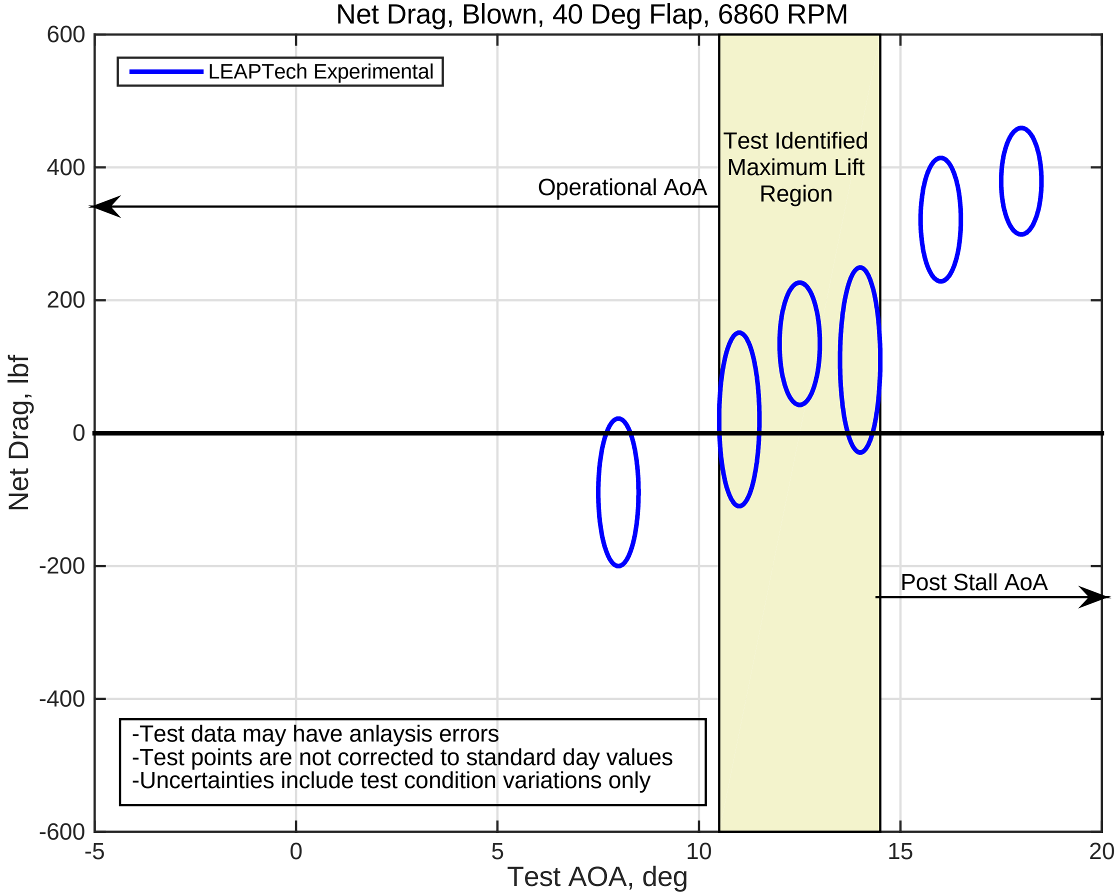

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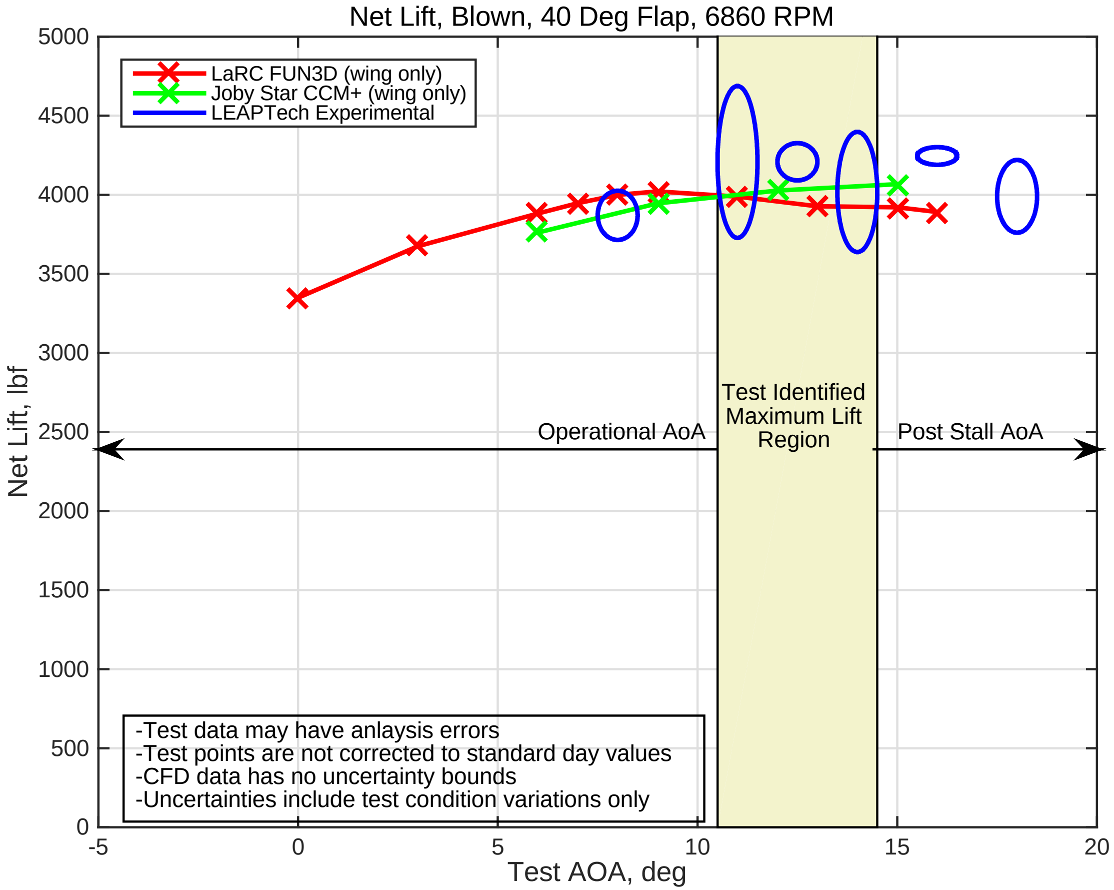

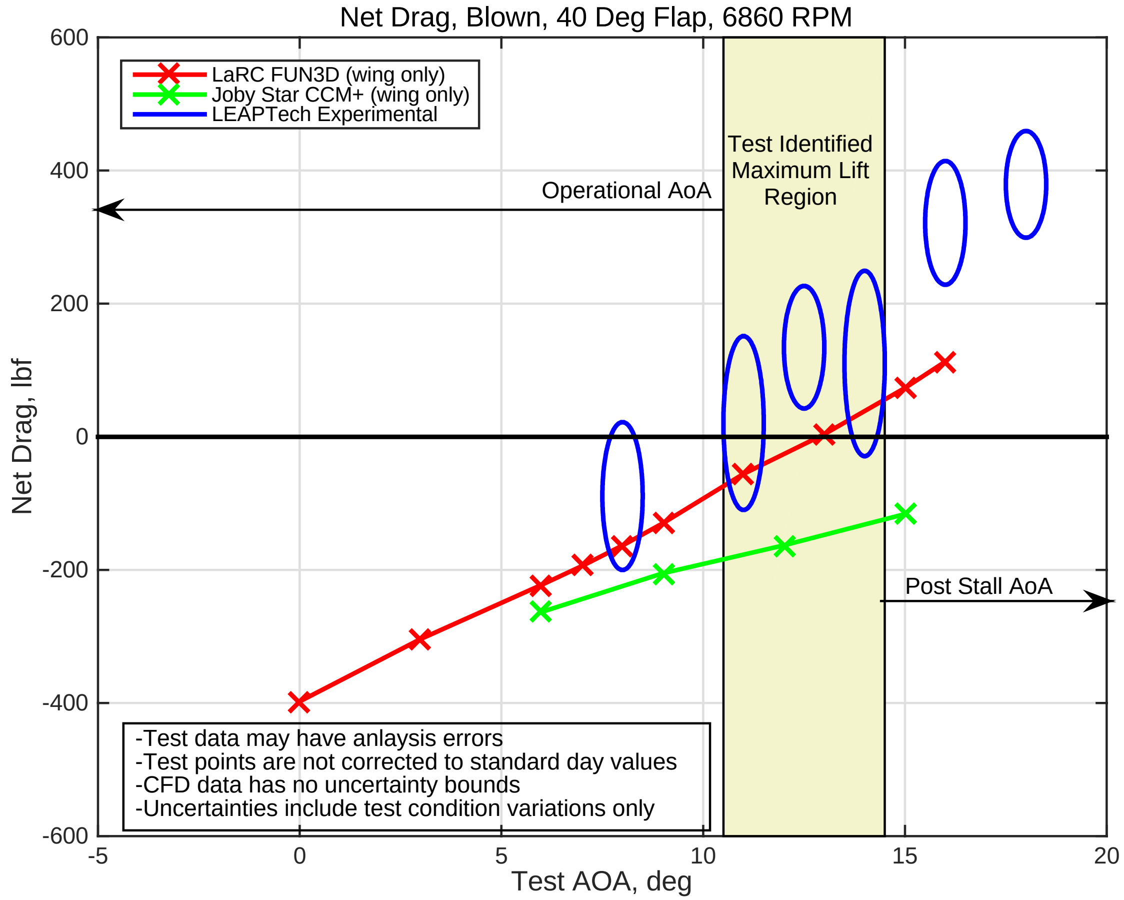

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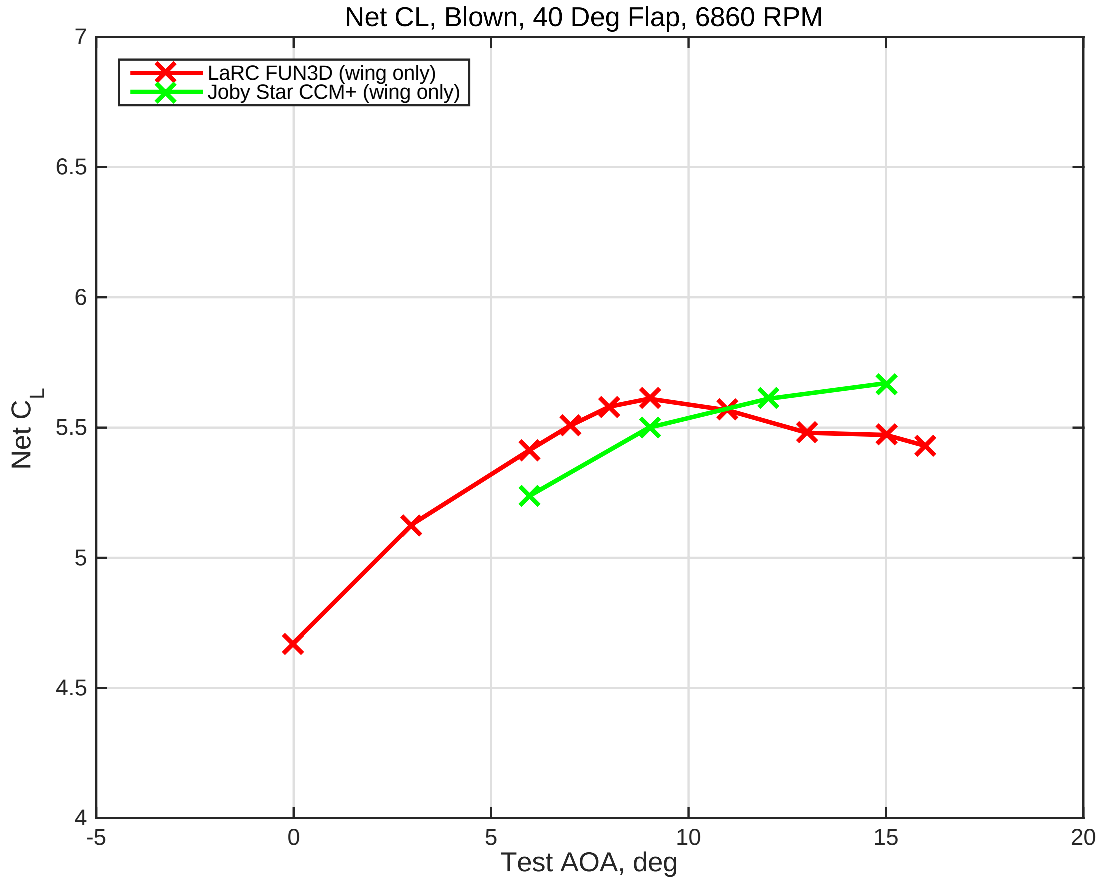

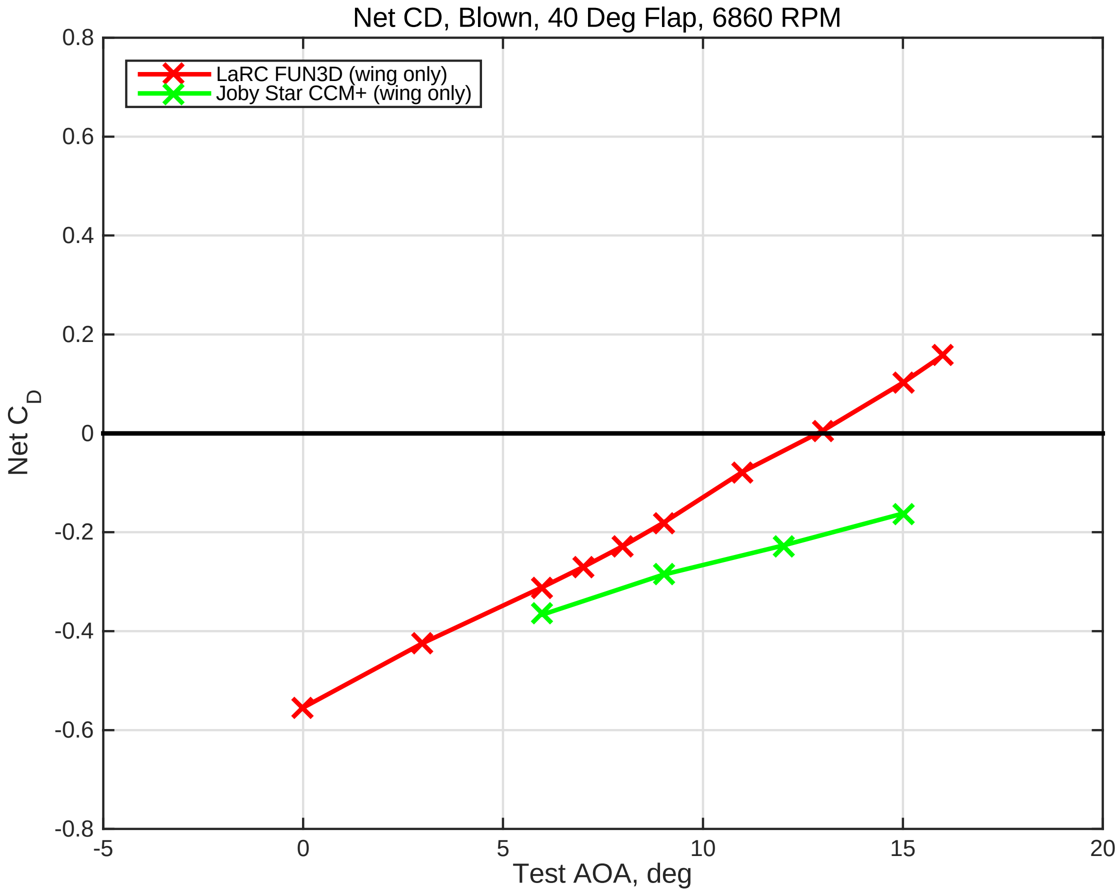

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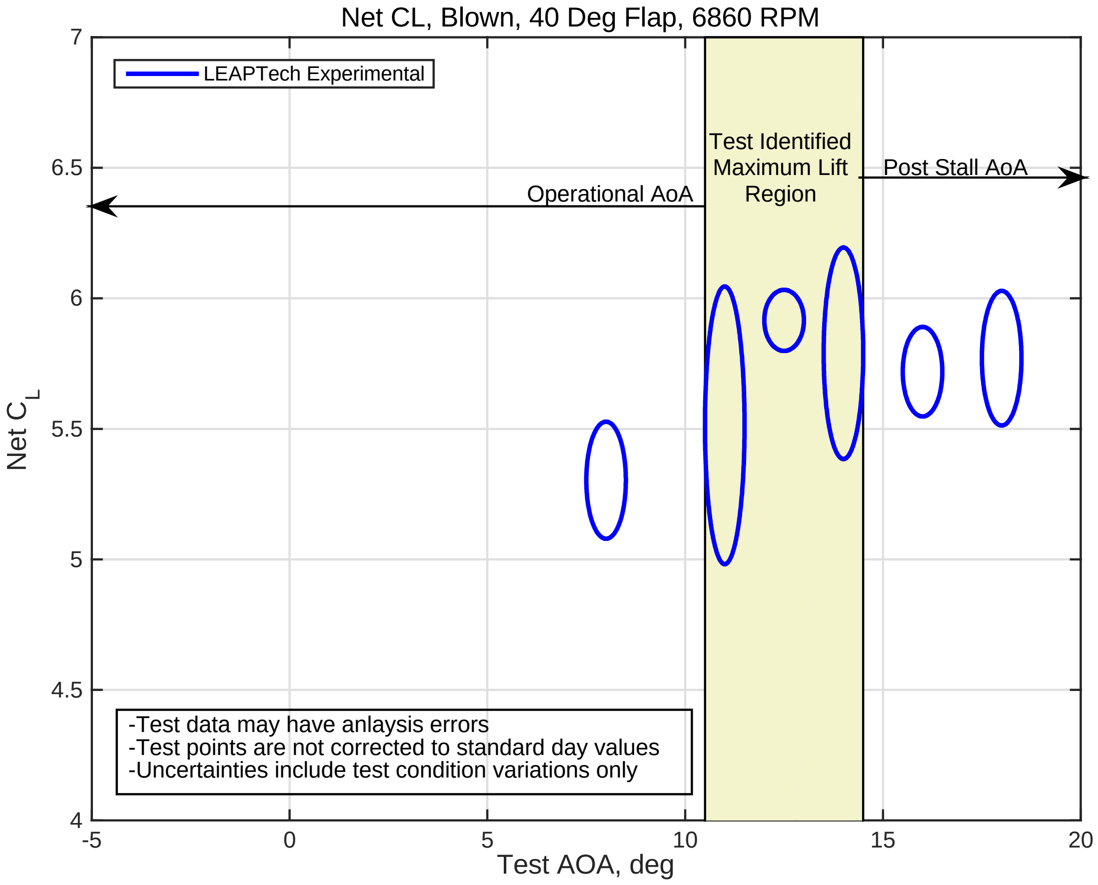

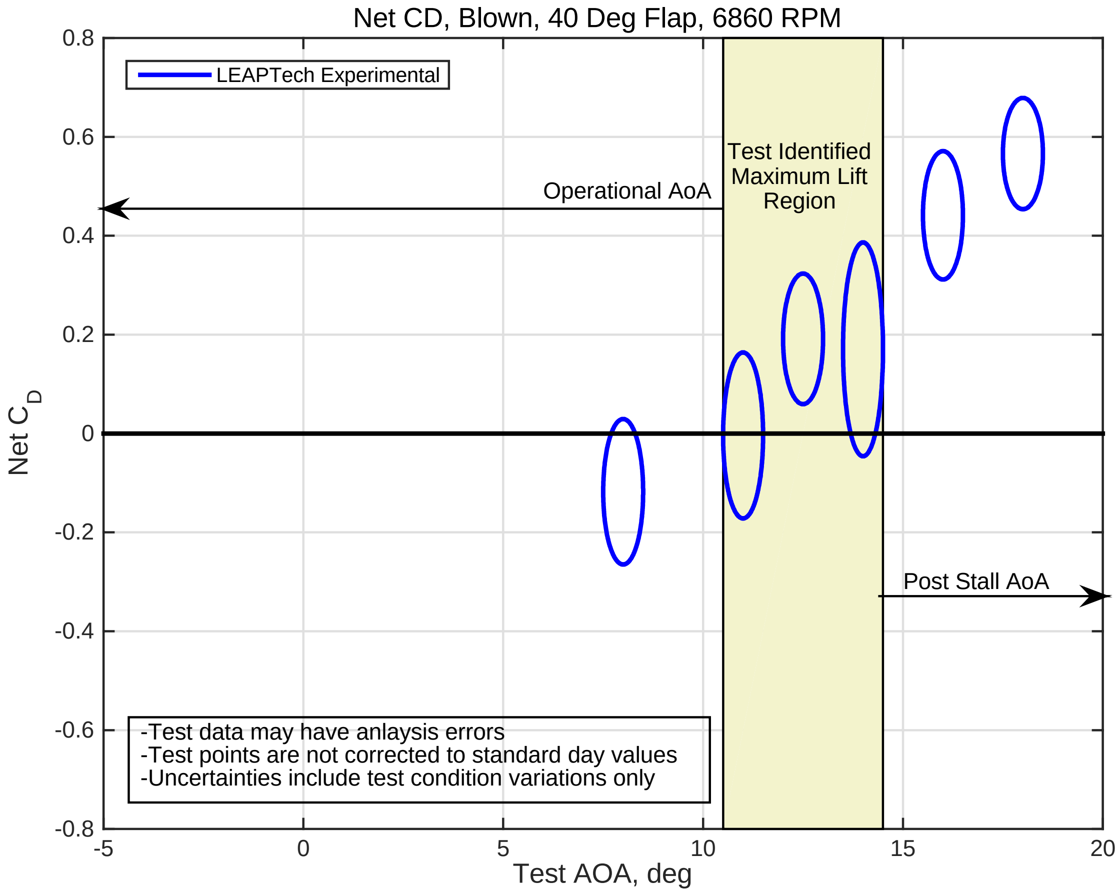

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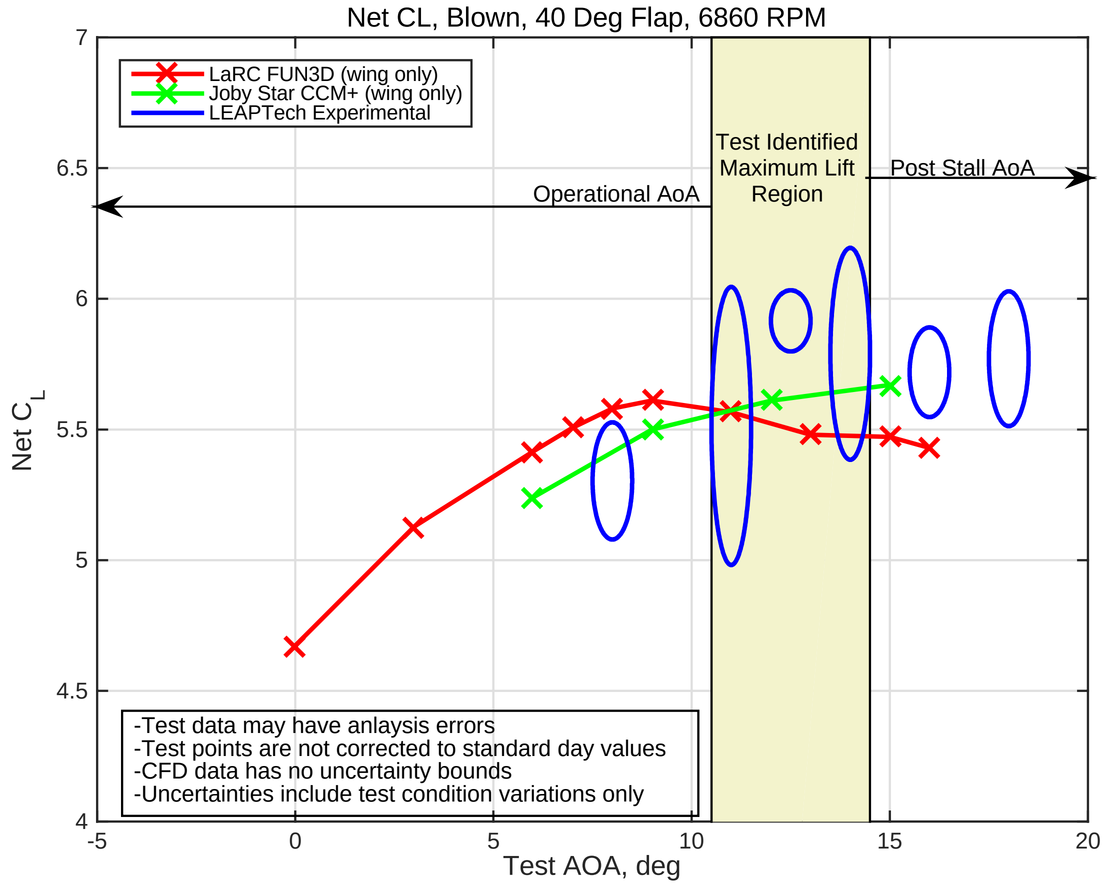

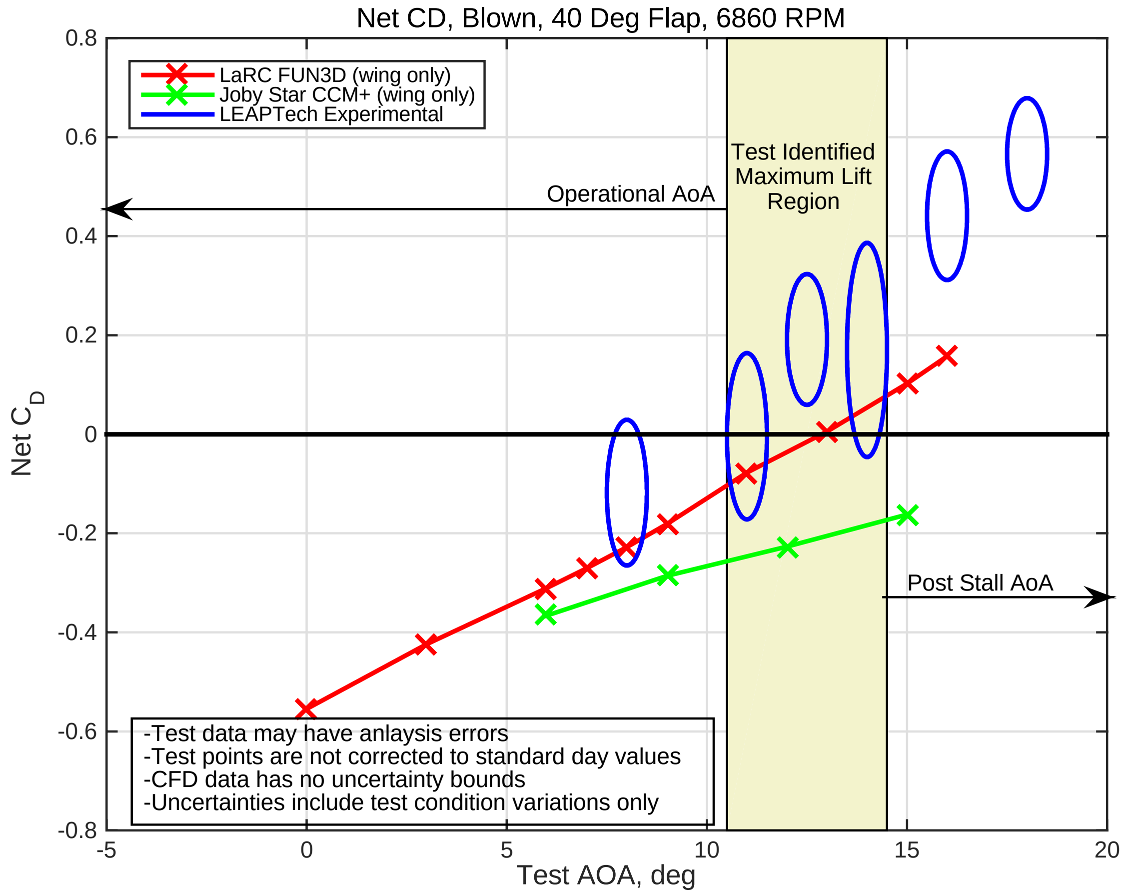

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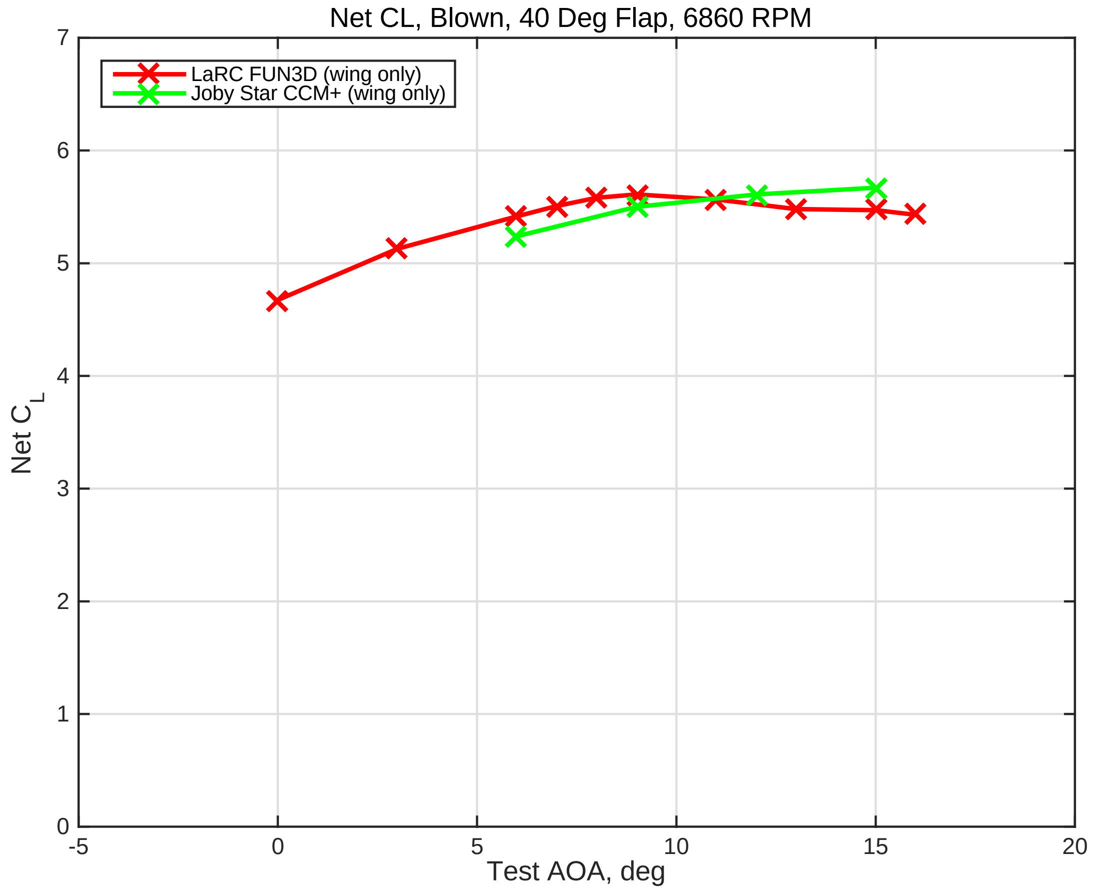

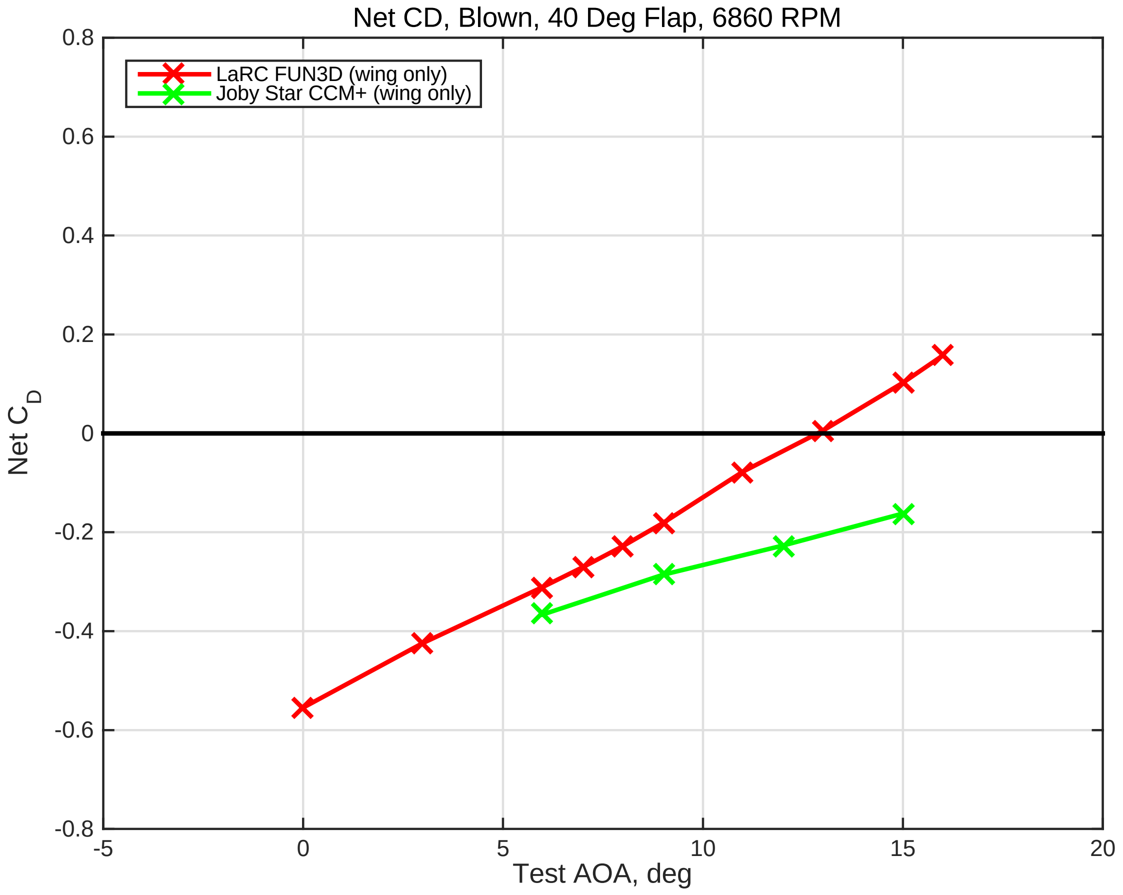

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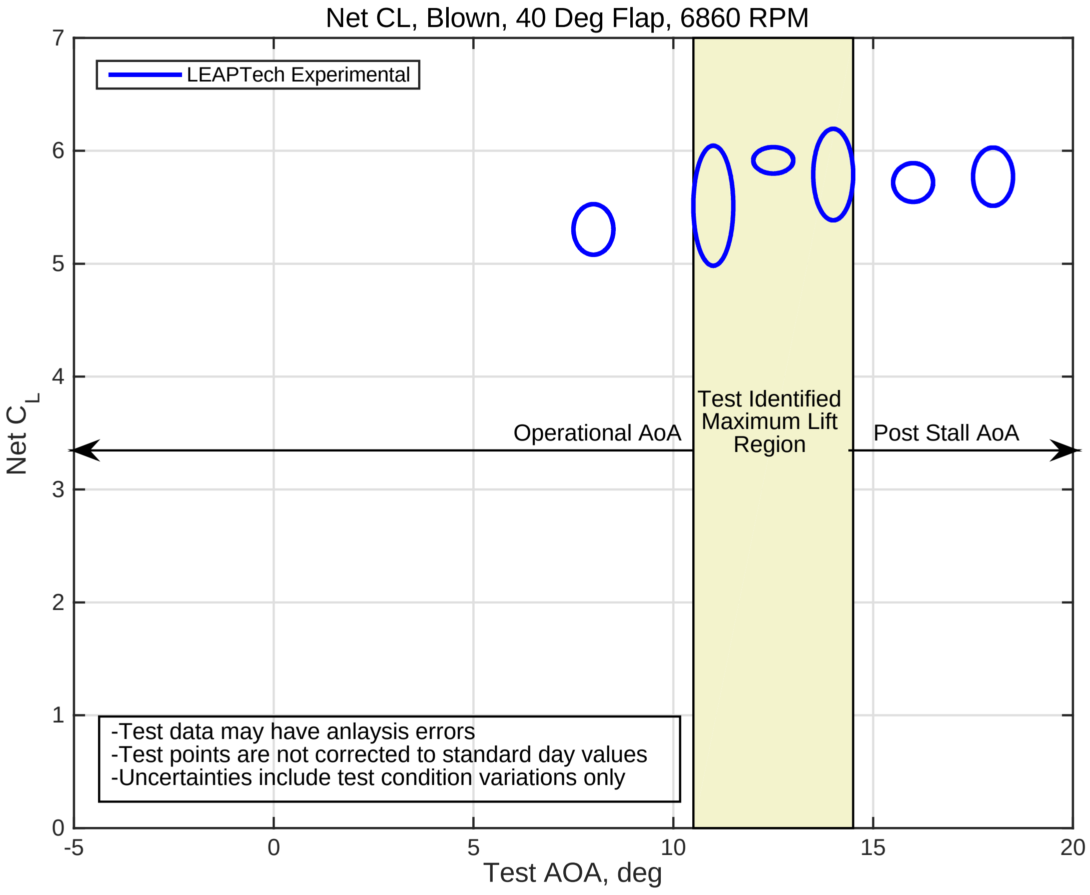

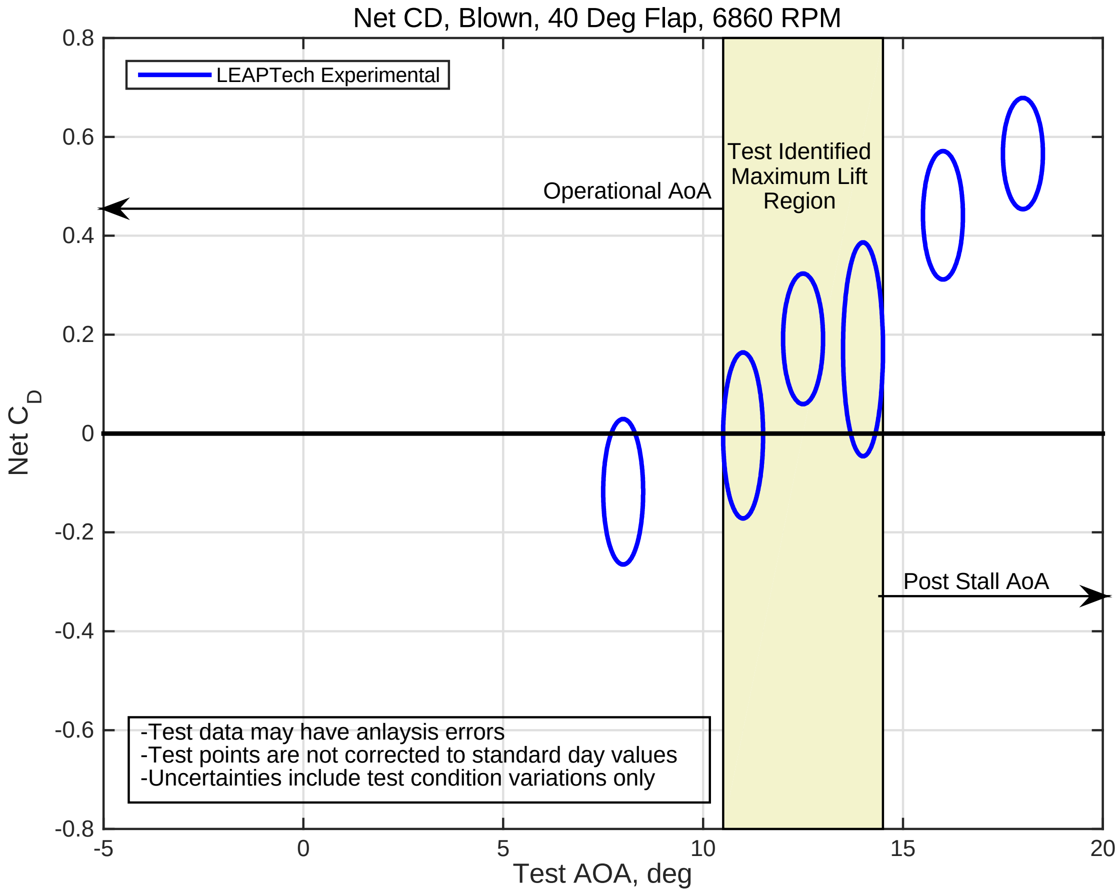

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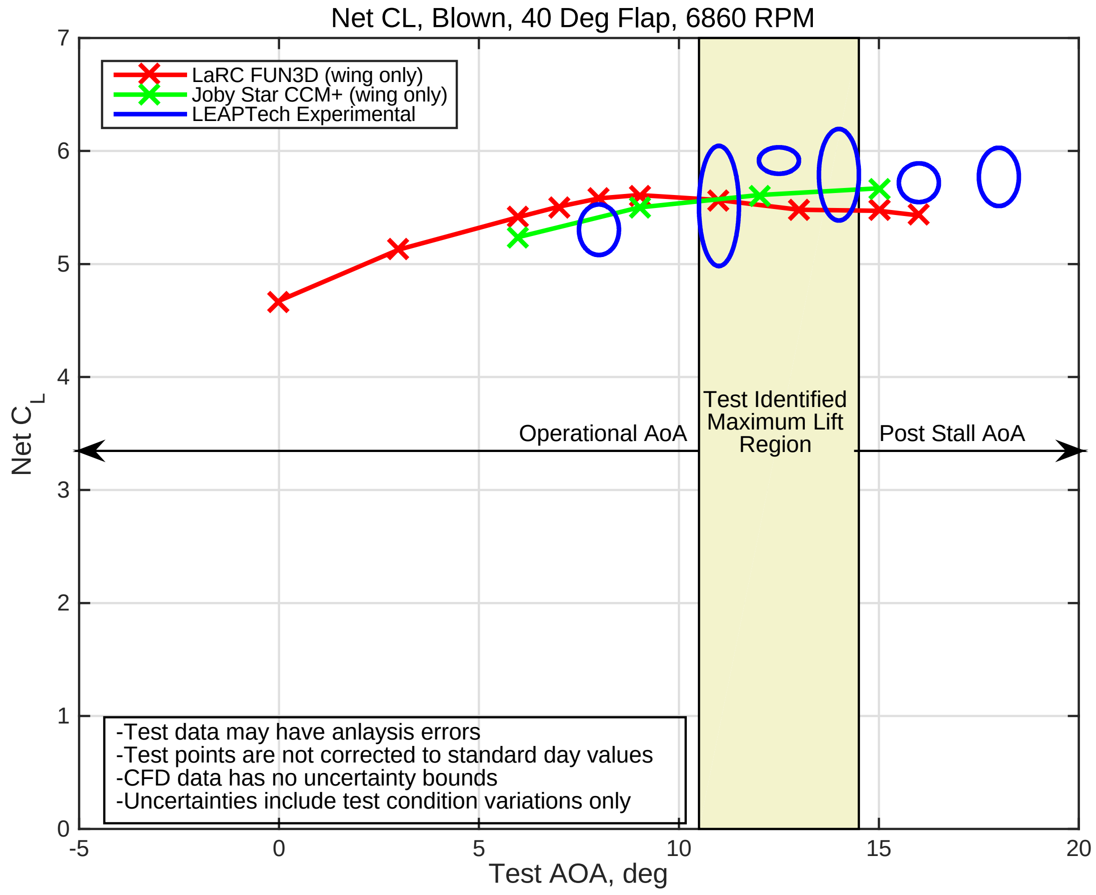
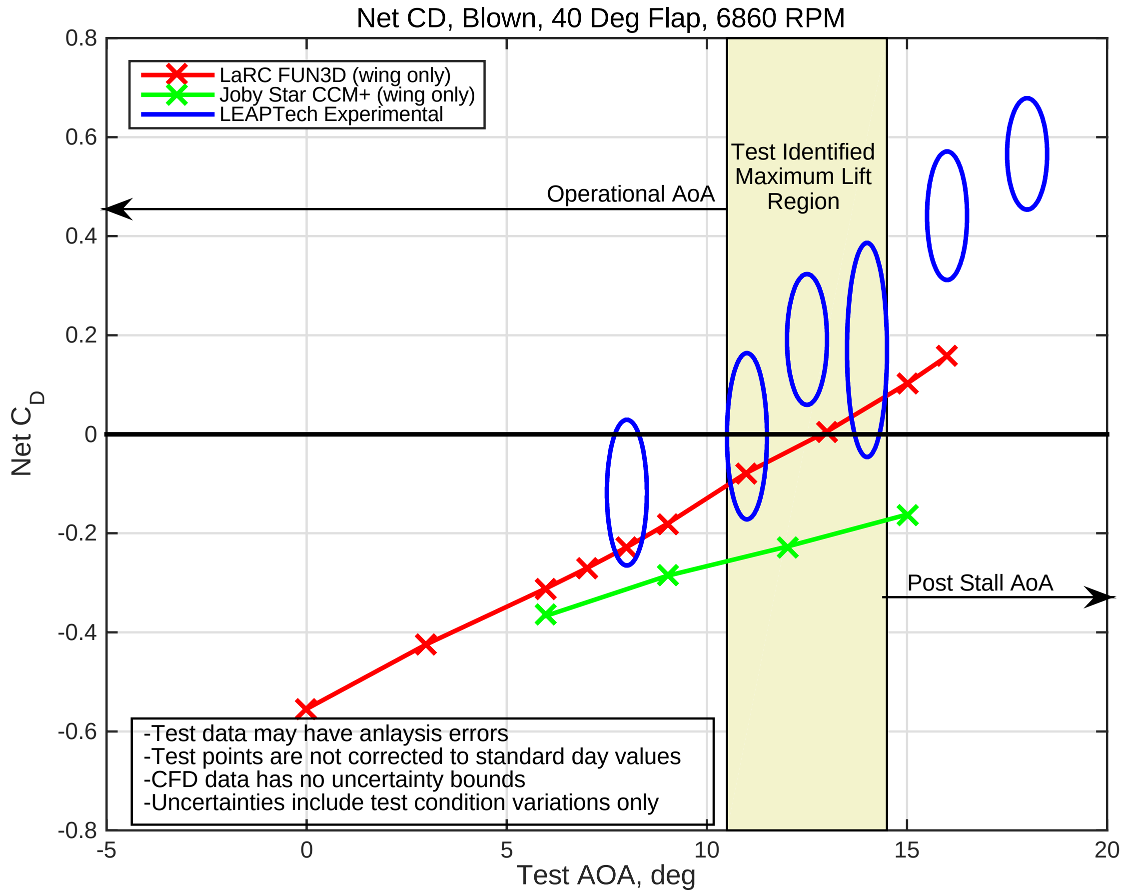
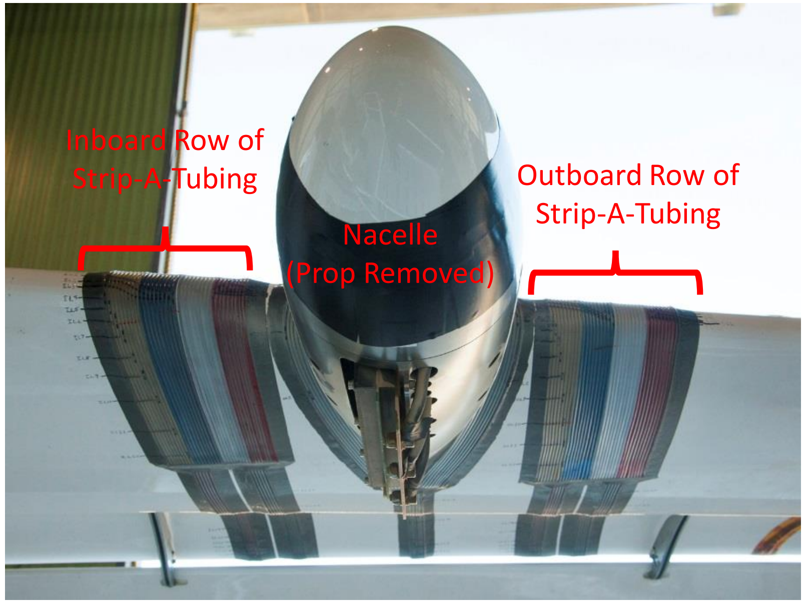
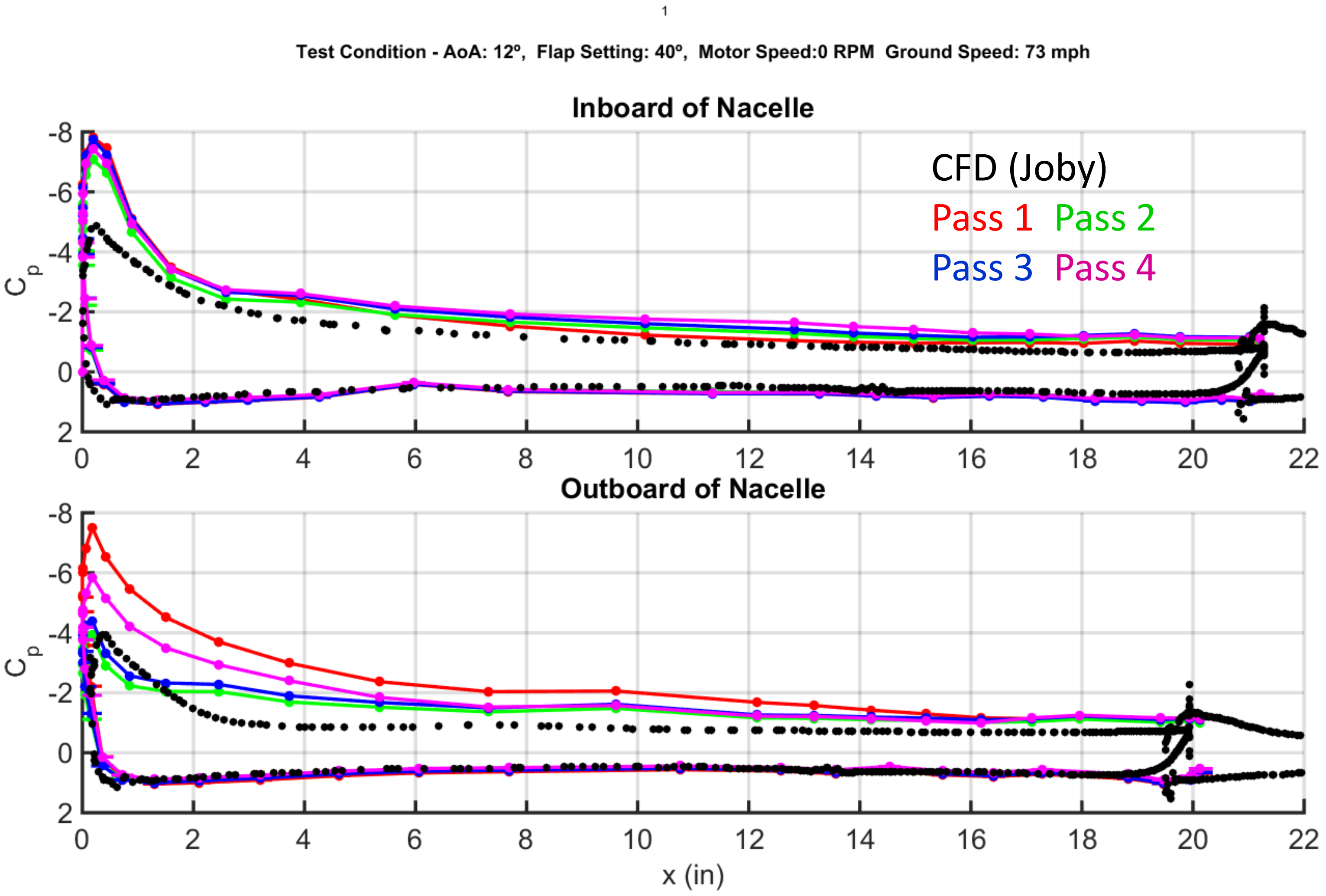




Looking Aft on Left Wing at Motor 5

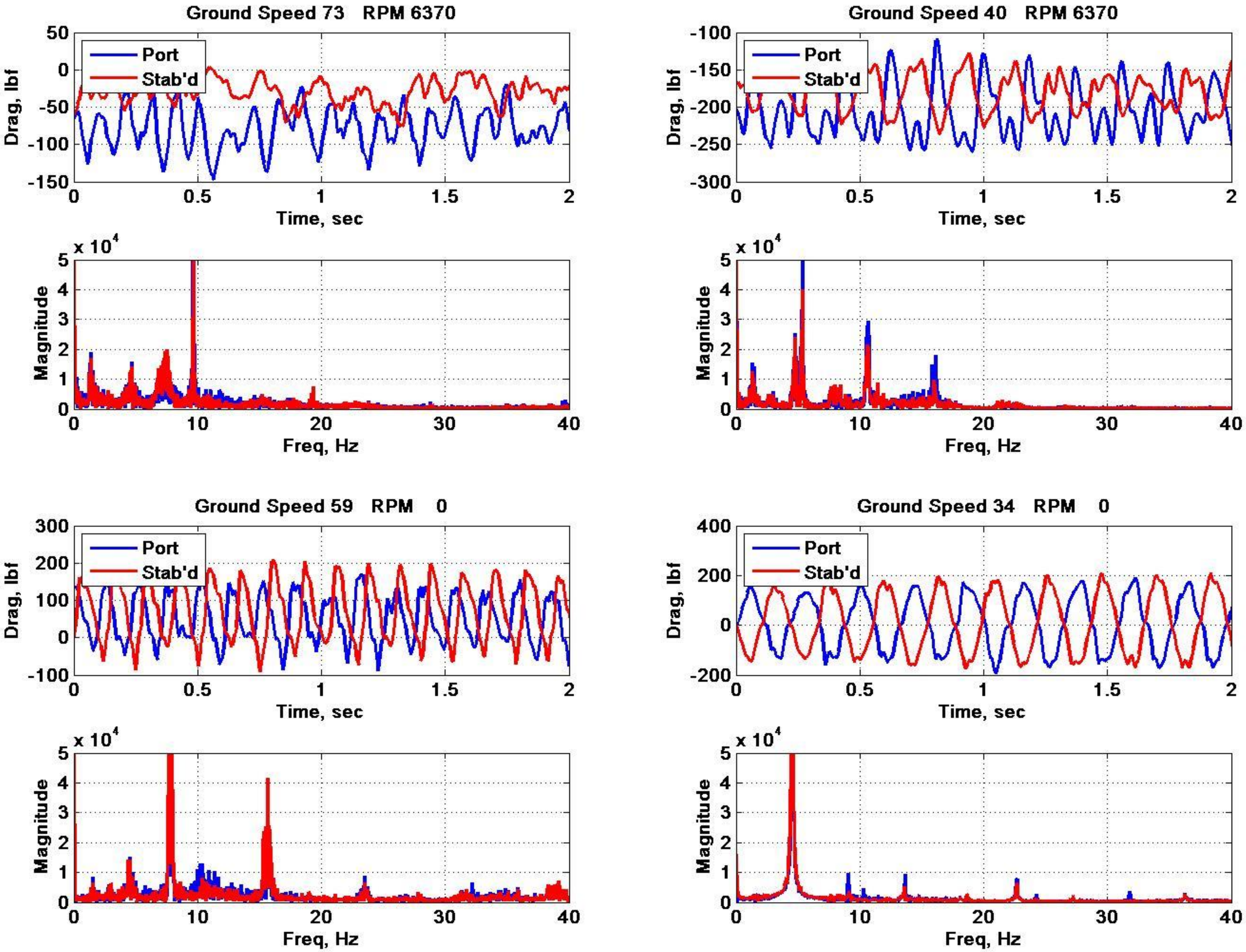


Local-Flow Details --
Wing Surface Pressure Measurement



- Bottom-surface wing pressures reasonable agreement with CFD
- Upper-surface pressures significant disagreement with CFD
- Pressures on inboard “windward side” of nacelle are repeatable
- Pressures on outboard “leeward side” of nacelle are not repeatable

Drag Measurements – Modal Interaction (Flutter?)



- Modal survey identified structural modes at 1.4, 4.6, and 5.4 Hz
- Harmonic content indicates nonlinearities
- Frequency of unknown forcing function energizes structural modes at 59 MPH and 34 MPH
- Unknown mode injects energy into the structural mode – “flutter”?
- Where does “missing” drag load go – into lateral load cell?

Recommendations

- Consider LEAPTech as a valuable lesson in identifying Propulsion-Airframe Interaction areas requiring additional investment

- Invest in a foundational (back-to-basics) approach, characterized by:
    - “What are the right analytical approaches to the problem?”
    - “What are the experiments that can supply tool-validation data?”

Recommendations

Some specific foundational building-blocks:

1. Perform CFD sensitivity studies of LEAPTech wing to:
   - CFL, gridding, . . .
   - Nonzero sideslip
   - Thrust asymmetry
   - Ground effect

2. Find measured performance data sets for a LEAPTech-scale or SCEPTOR-scale propeller and use for:
   - CFD validation test cases
   - AIRVolt experimental validation test cases

3. Build an AFRC-maintainable "Tool Kit" to go from …
   - a point-cloud scan of propeller to …
   - a CAD model suitable for CFD and other propeller analysis tools, to …
   - predictions of thrust and torque performance.

Backup Slides

Veldhuis Wind Tunnel Data Sets

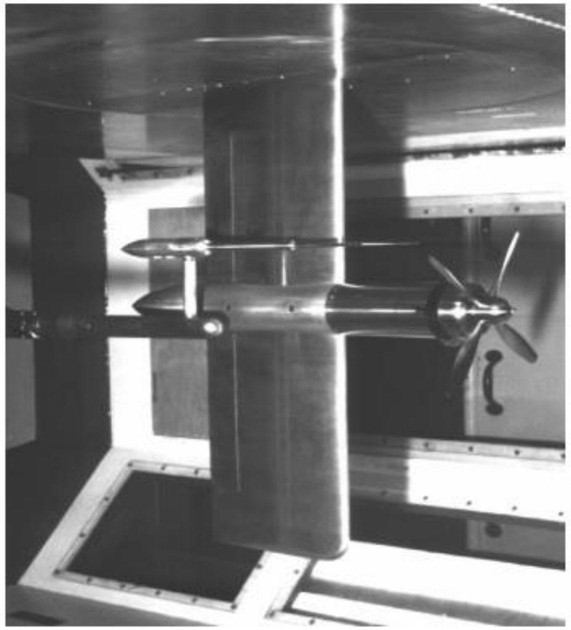


Figure 5.6: *Model PROWIM, installed in the LTT with a five hole probe mounted directly behind the propeller.*

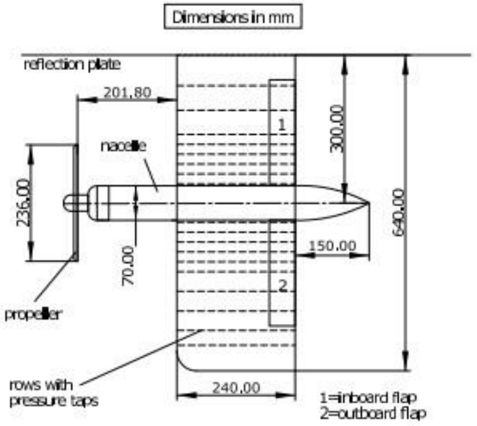


Figure 5.7: *Dimensions of the PROWIM model; Top View.*

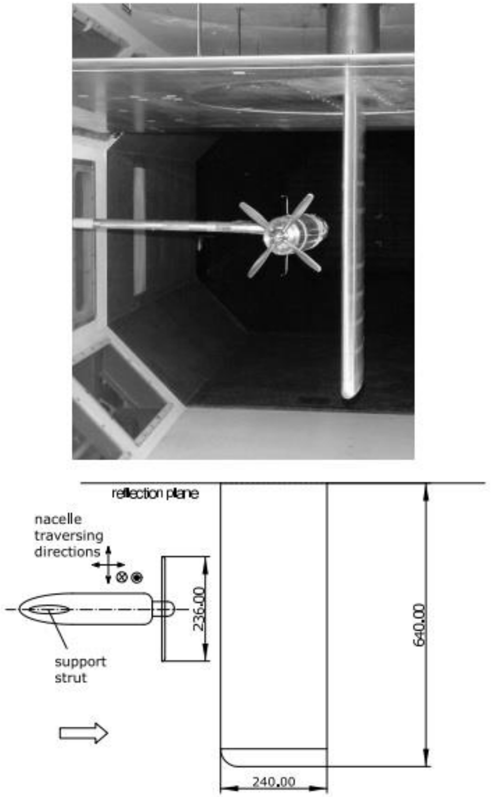
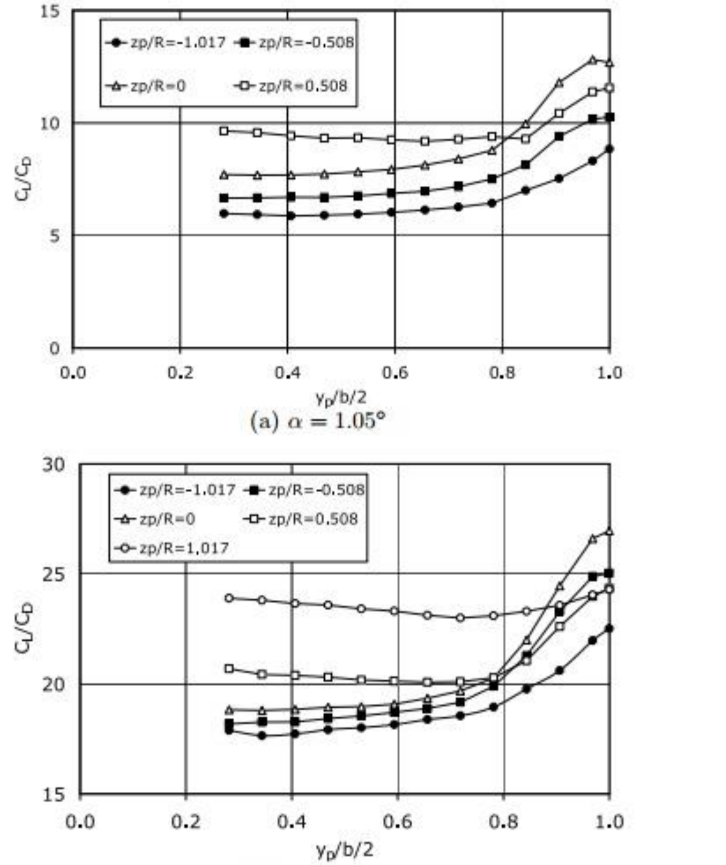


Figure 5.9: *Layout and dimensions of the APROPOS model (in mm).*

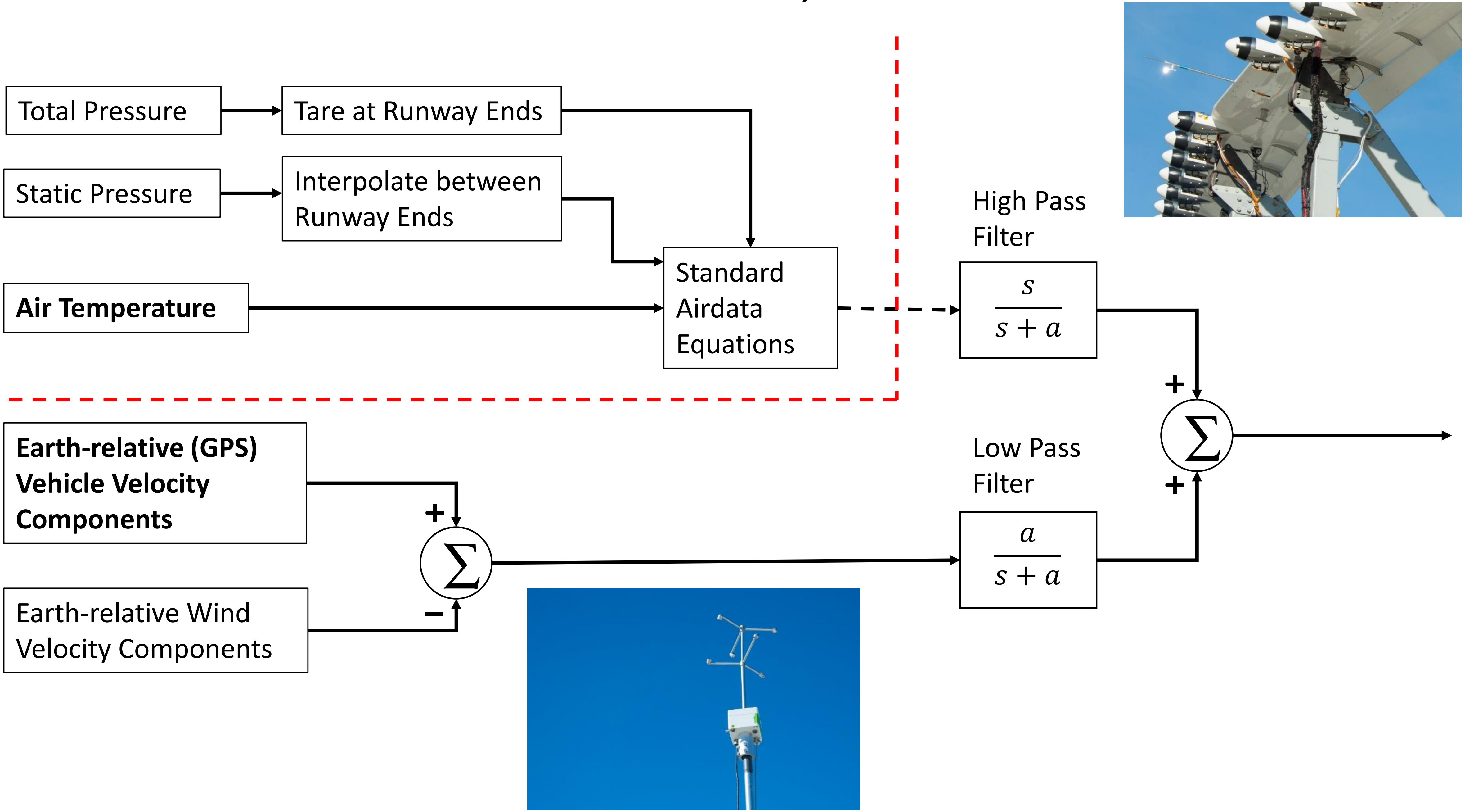


(a) $\alpha = 1.05°$

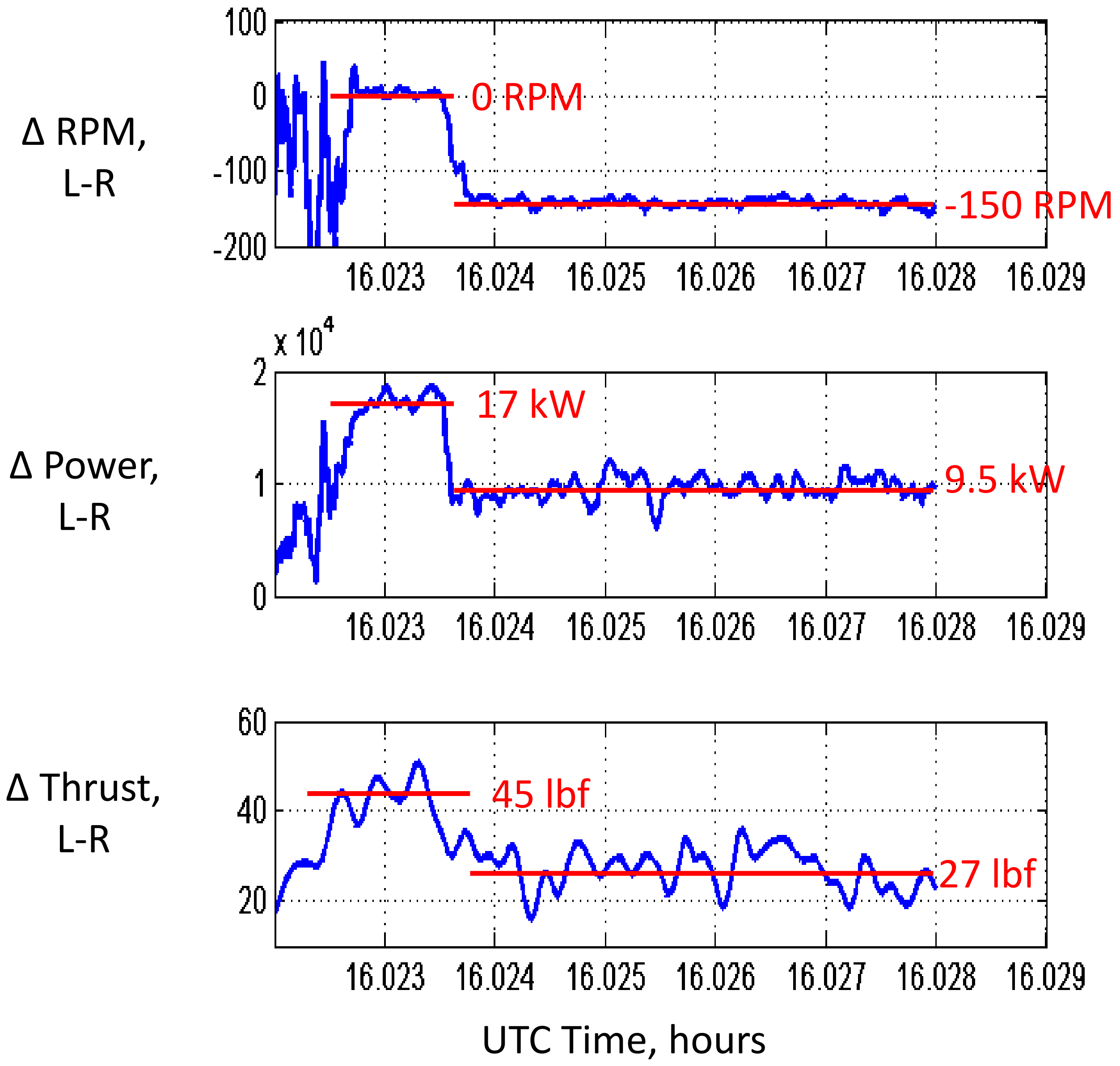
(b) $\alpha = 4.2°$

Figure 5.25: *Effect of the propeller spanwise location, y_p, on the lift/drag ratio of the APROPOS wing for several vertical propeller locations, z_p; $J = 0.92$; $T_c = 0.025$; $\alpha_p = 0°$.*

Airdata Estimation System



Attempt to Symmetrize the Thrust

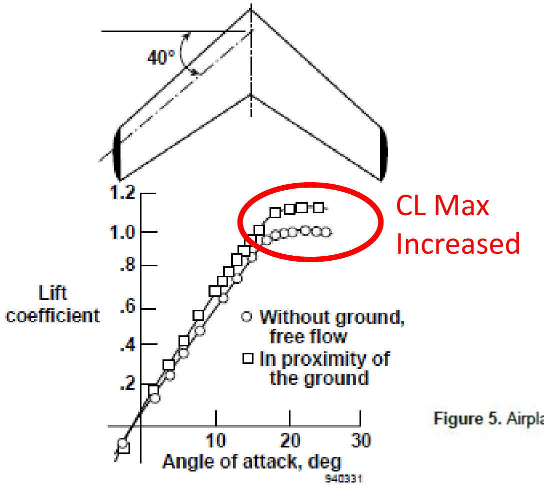


- Had test points in place to run left-wing motors at different RPM than right wing
- No realtime knowledge of thrust asymmetry, so it was a a cut-and-try approach
- Only got 1 test point before motor/controller failures terminated the experiment
- Δ RPM of approx. 375 RPM would have symmetrized the thrust

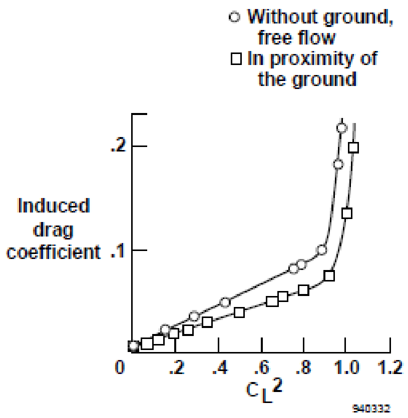
Ground Effect

Effect on CL Max

Corda



(a) Lift.



(b) Drag.

G650 Accident Report

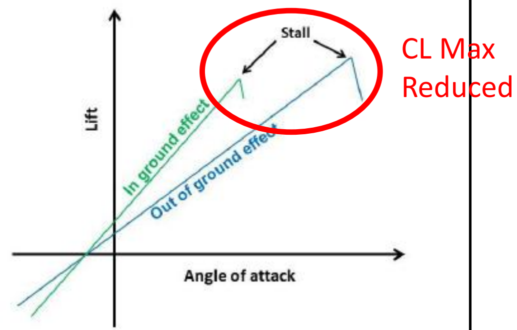


Figure 5. Airplane lift versus angle of attack in and out of ground effect.

Effect of Height above Ground (Bowers & Curry)

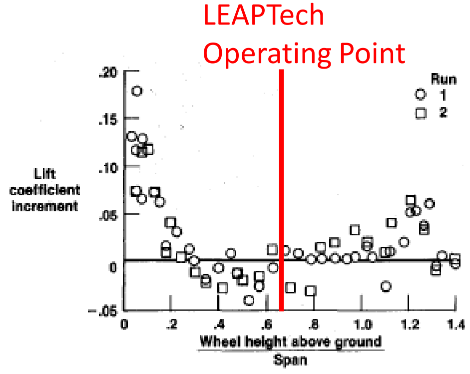


Fig. 4 Ground-effect lift coefficient increment; CID/720 at 40° flap.

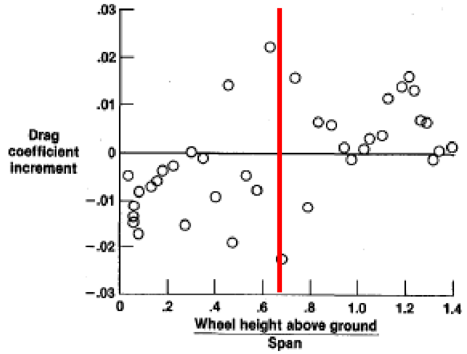


Fig. 6 Ground-effect drag coefficient increment; CID/720 at 40° flap.

Effect with Blown, Flapped Wing

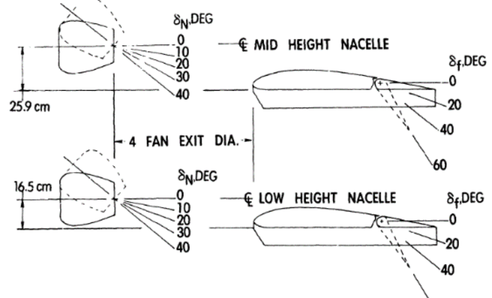


Figure 4.- The wing-in-ground effect model, nacelle and wing details.

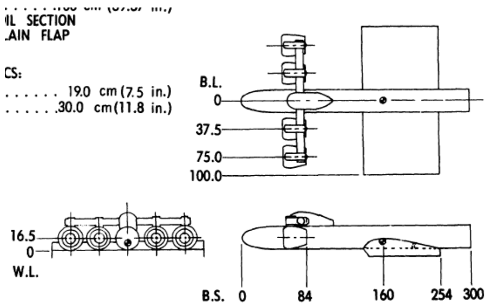


Figure 3.- Wing-in-ground effect (WIG) model.

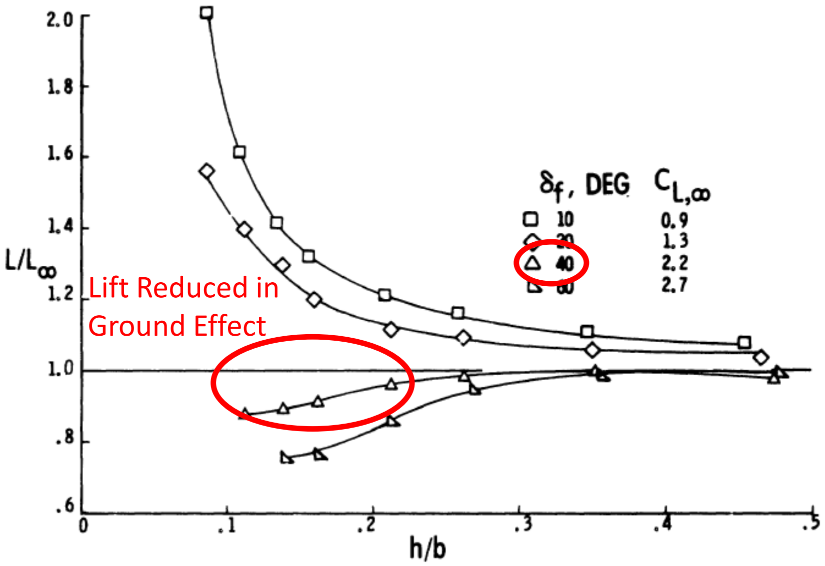
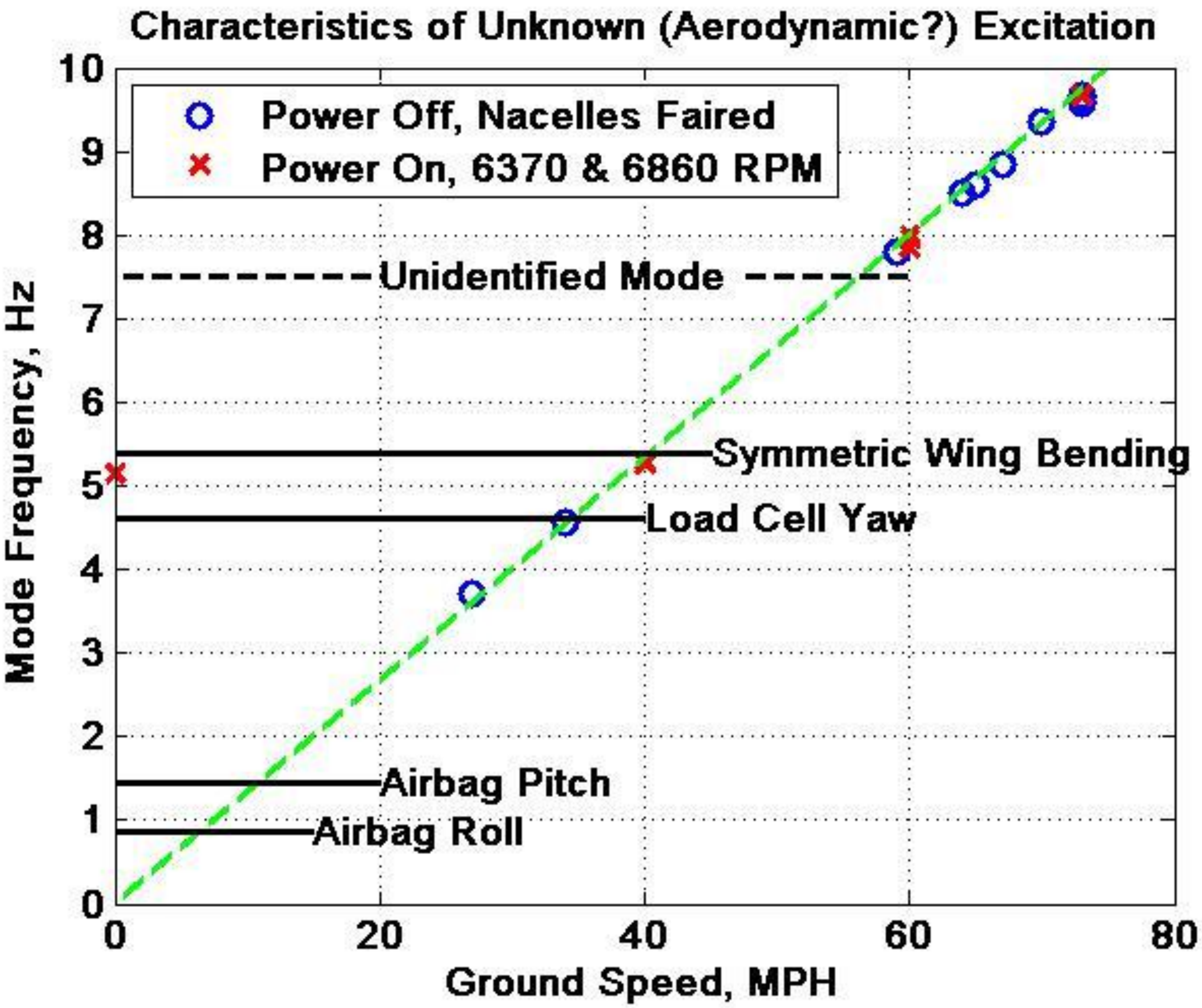


Figure 28.- The effect of flap deflection on the ratio of lift in-ground effect to lift out-of-ground effect, $\delta_N = 19^0$, $\alpha = 0^0$, $C_T = 0.7$, $C_\mu = 0.12\ C_T$.

Observed Mode of Unknown Origin



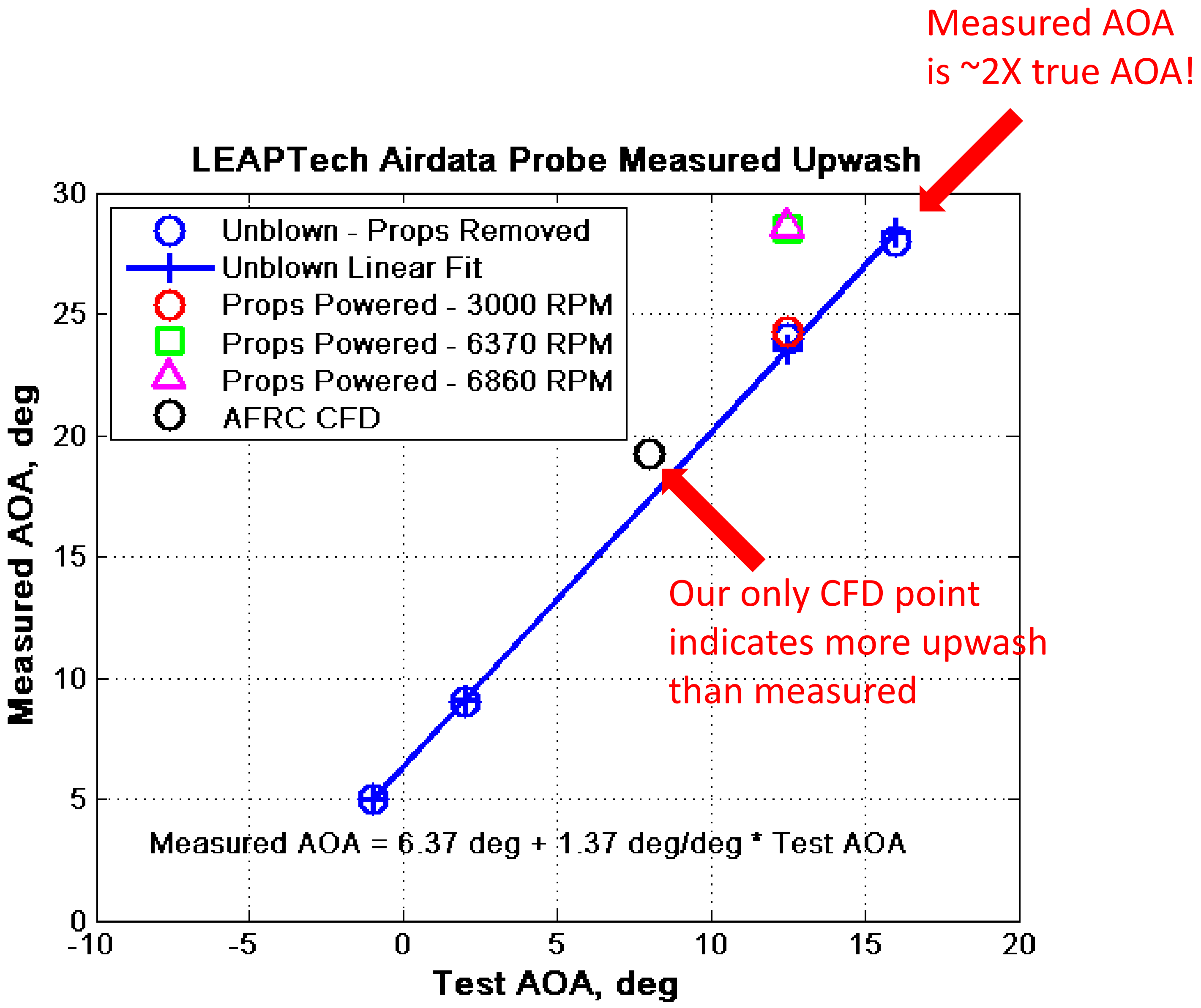
- Frequency linearly proportion to ground speed (or airspeed), and intersects the origin
- Frequency is independent of motor/propeller power setting
- Mode is antisymmetric
- Frequency and phase correspond to 2D vortex shedding from a 2.2-ft wide vertically-oriented structure

$$S = fd/V$$
$$d = SV/f$$
$$d = 0.2 * \frac{107\,\frac{ft}{s}}{\left(9.6\,\frac{cycles}{s}\right)} = 2.2\ ft$$

- The source of this excitation remains unknown

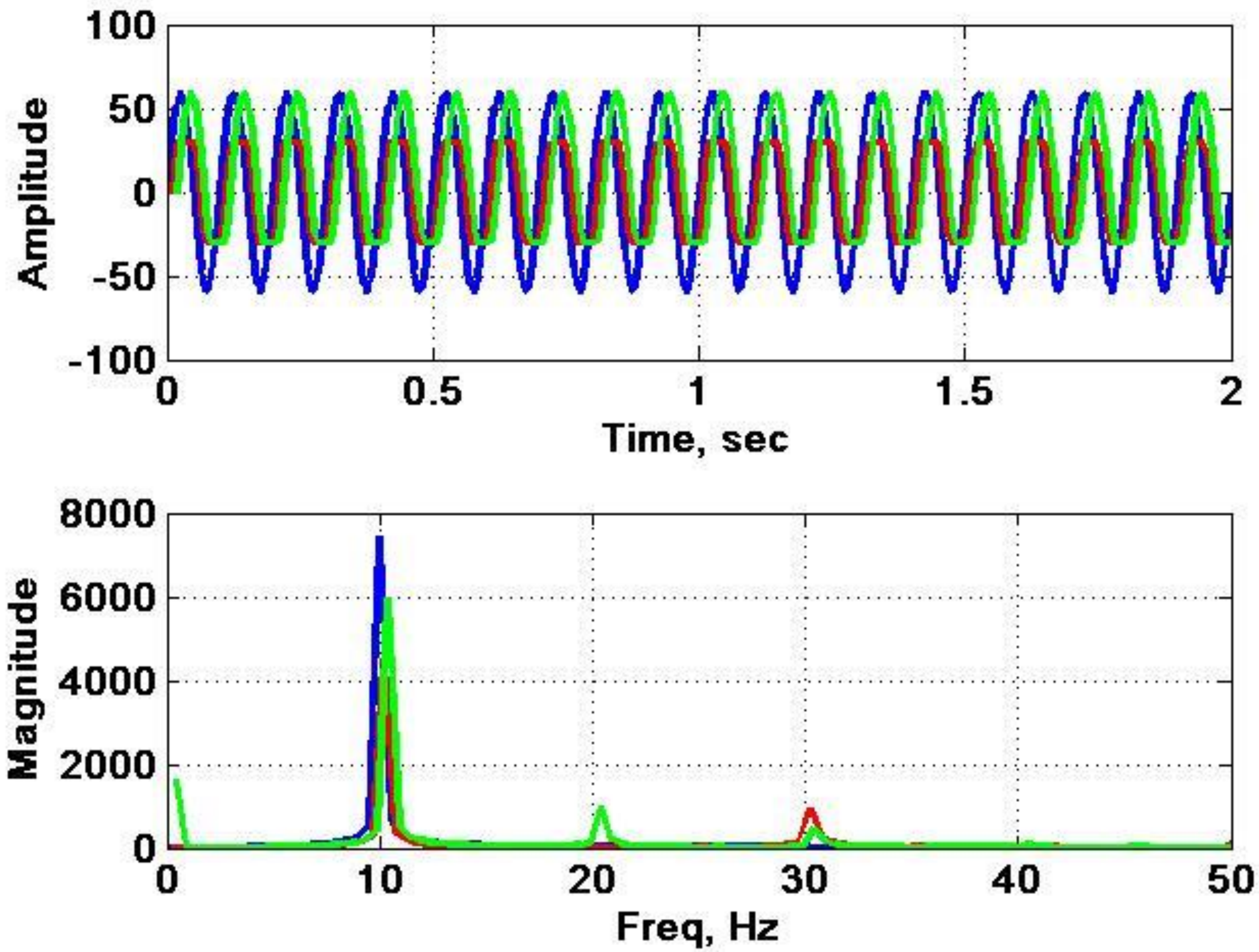
Local Flow Details – CFD versus LEAPTech Lakebed Test

- The “What” -- Macro observables (total lift and drag) indicate CFD-to-Experimental discrepancies
- The “Why” -- Local flow detail observables (flow angles, section Cp) may provide insight



Harmonics and DC Offset as Symptoms of Nonlinear Dynamics

- Synthetic data for illustration
- 10 Hz sine wave sampled at 125 SPS (representative of LEAPTech)
- Clipped (partially rectified), symmetrically and asymmetrically
- Asymmetric clipping yields DC component to signal
- Nonlinear behavior in time domain appears as harmonic content ***and DC component*** in frequency domain



Harmonics and DC Offset as Symptoms of Nonlinear Dynamics

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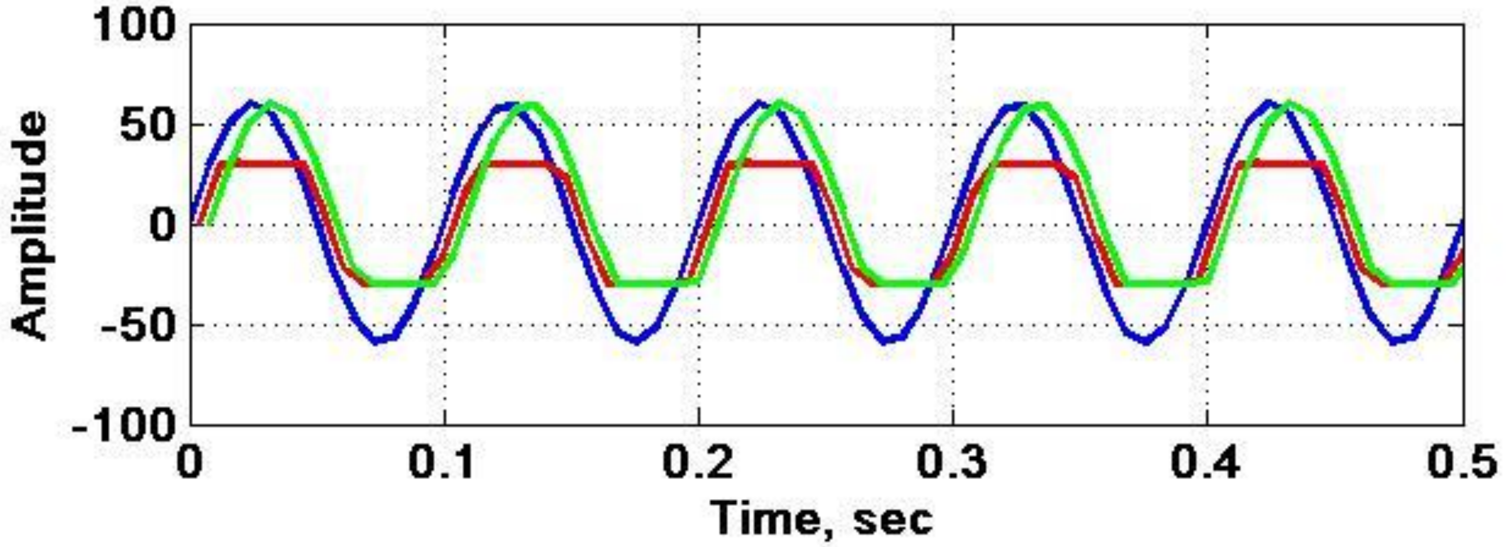
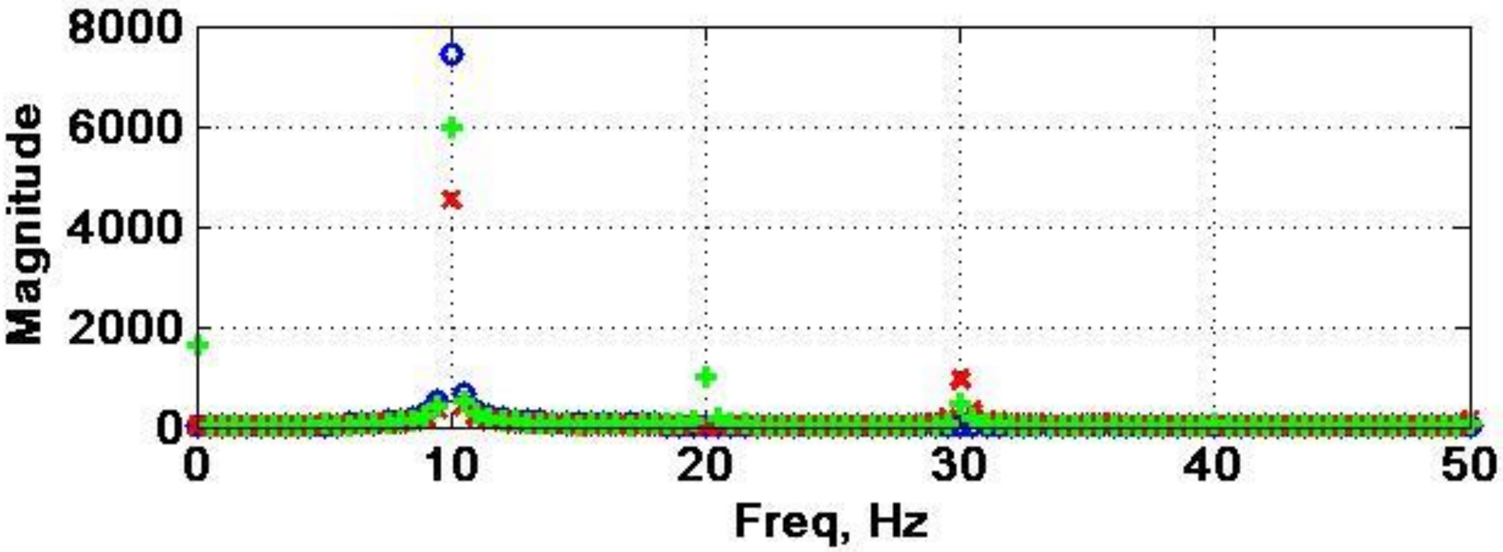




Expected CL for Unblown, Flapped Wing

Hoerner

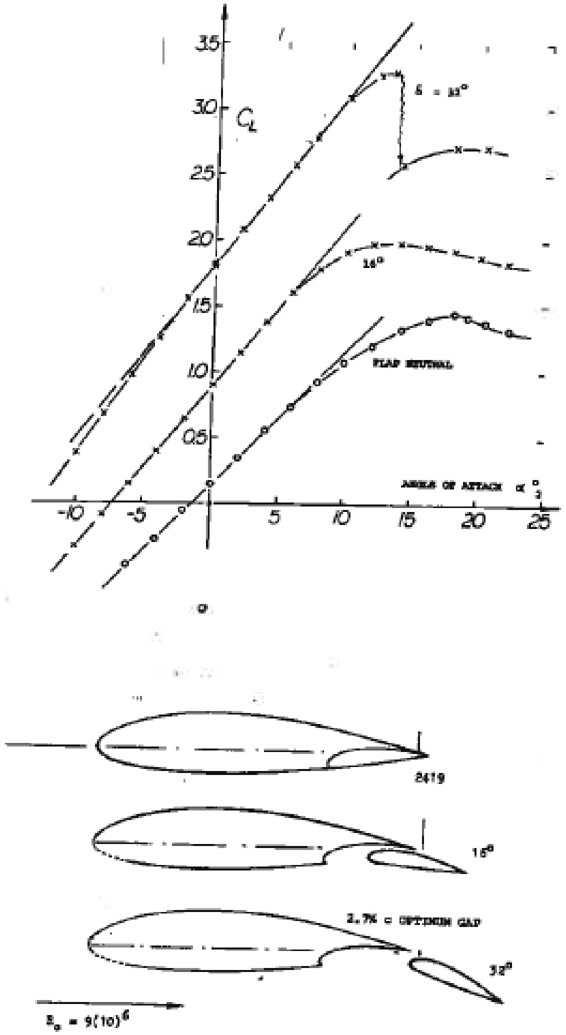
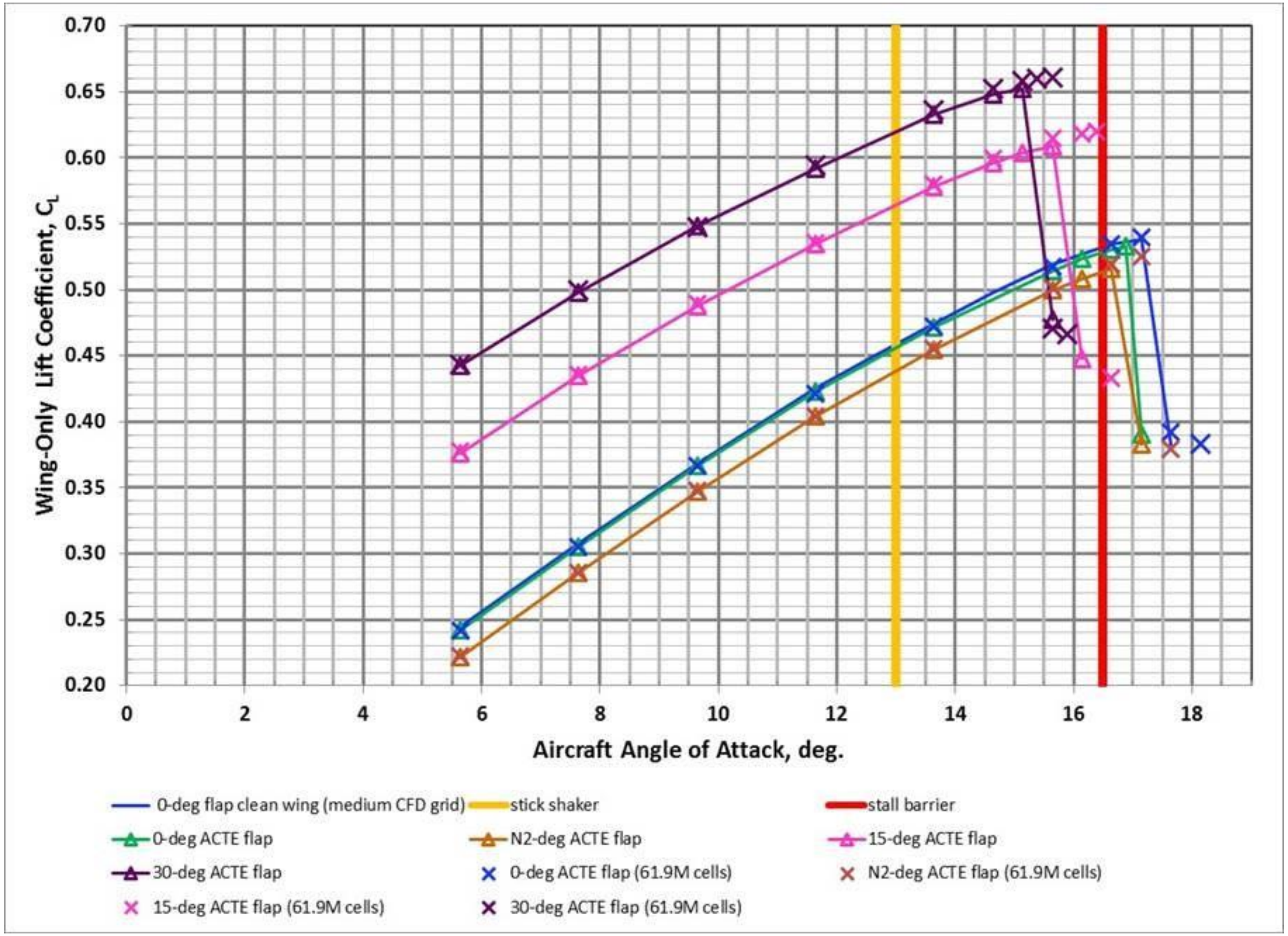


Figure 17. Example for a 30% Fowler flap, tested (20,g) between walls, in three positions.

ACTE
(Note: incorrect Sref)



Previous Work in Propeller-Wing Interaction Wind Tunnel Testing with CFD Comparison

Propeller Wing Aerodynamic Interference

Proefschrift

ter verkrijging van de graad van Doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof. dr. ir. J.T. Fokkema
in het openbaar te verdedigen ten overstaan van een commissie,
door het College voor Promoties aangewezen,

op dinsdag 28 juni 2005 om 15:30 uur
door

Leonardus Louis Maria Veldhuis
Vliegtuigbouwkundig ingenieur

FFA TN 1990-24

FFA TN 1990-24

FLYGTEKNISKA FÖRSÖKSANSTALTEN

The Aeronautical Research Institute of Sweden

LOW SPEED WIND TUNNEL INVESTIGATION OF PROPELLER SLIPSTREAM AERODYNAMIC EFFECTS ON DIFFERENT NACELLE/WING COMBINATIONS

Part 2: Propeller Slipstream Flow Field Surveys (Velocity Components, Dynamic, Total and Static Pressure Distributions) at Zero Angle of Attack and High Power

by
Ingemar Samuelsson

99042

42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
9 - 12 July 2006, Sacramento, California

AIAA 2006-4969

Unsteady CFD Simulations of Propeller Installation Effects

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DLR, German Aerospace Center
Institute of Aerodynamics and Flow Technology
Lilienthalplatz 7, 38108 Braunschweig, Germany

A series of unsteady CFD simulations have been conducted for a set of generic isolated- and installed-propeller configurations at low-speed flight conditions. The propeller geometry investigated is a four-bladed design typical of those used on modern regional turboprop aircraft. The computations were performed with the unstructured DLR TAU-code and the numerical results are compared with experimental data obtained in a wind tunnel test campaign conducted in the 1980s. The results of the unsteady computations agree well with the available propeller slipstream data and surface pressure distributions measured in the wind tunnel. Additionally, a detailed analysis and comparison of the forces acting on the wing and the propeller is performed.

Samuelsson (Wind Tunnel) and Stuermer (CFD Comparison)

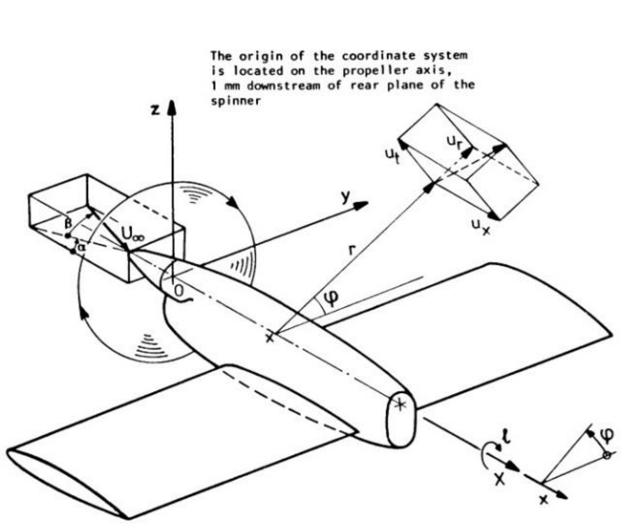


Fig. 4 Definition of coordinate system and nacelle forces and moments

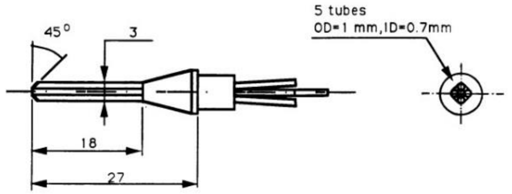


Fig. 5 5-hole probe layout

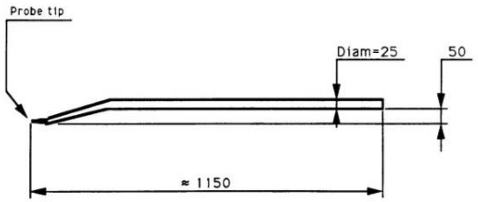


Fig. 6 5-hole probe cranked sting

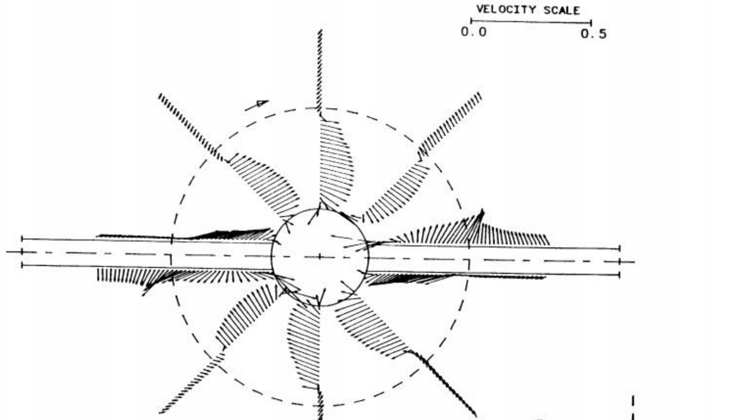
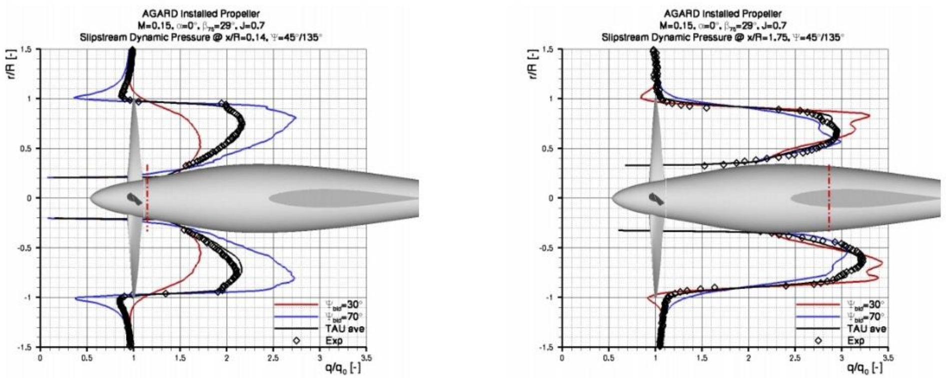


Fig. 60 Cross-flow velocity vectors in wing quarter chord plane. CONF2

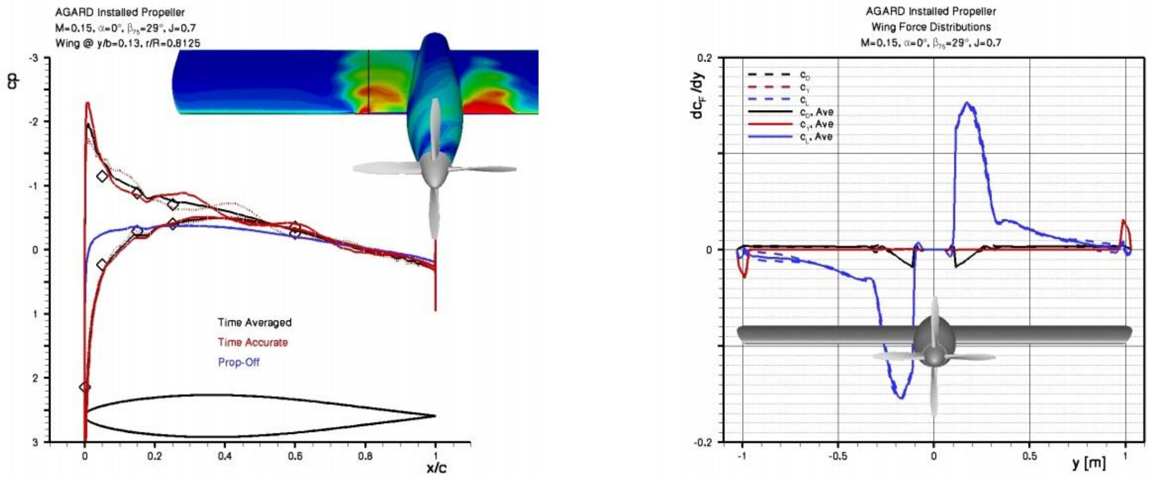
U_∞=48.72 m/s, n=6642.2 RPM, $\beta_{.75}$=29°, α=β=0°
C_F=0.255, J=0.688, C_T=0.246, C_P=0.250, η=0.677



(a) Dynamic pressure profiles @ $x/R = 0.14$

(b) Dynamic pressure profiles @ $x/R = 1.75$

Figure 4. Installed propeller slipstream development



(a) Wing pressure distribution

(b) Spanwise wing force distributions

Figure 5. Impact of the propeller slipstream on the wing